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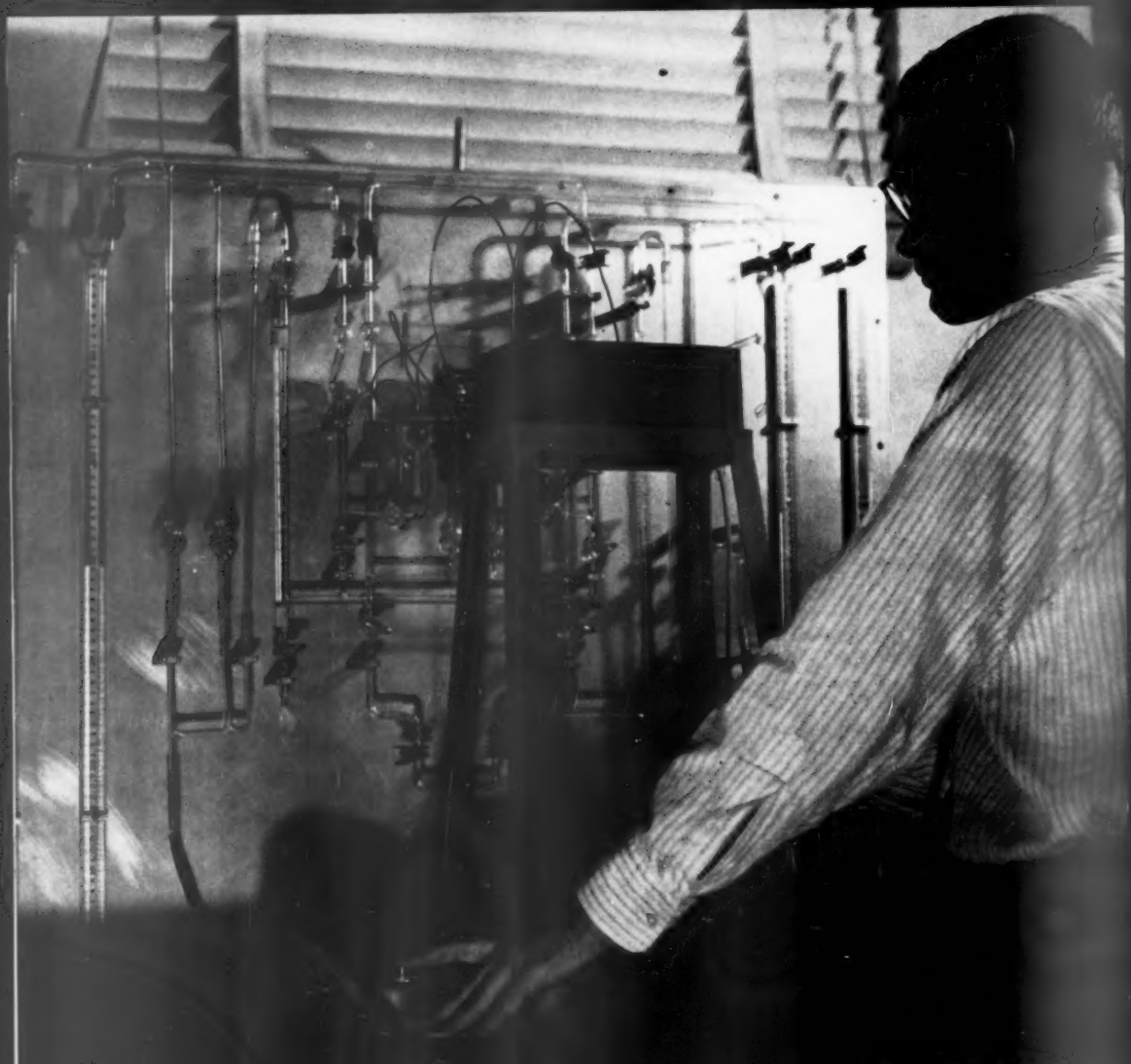
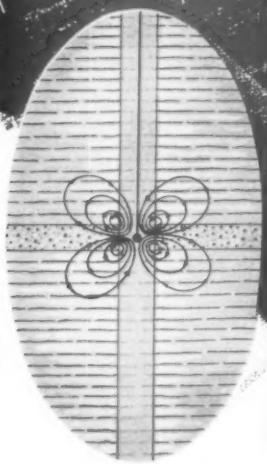
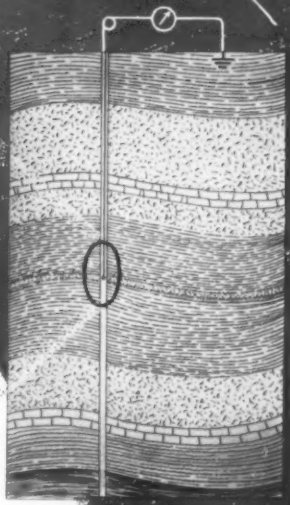


JULY, 1951

THE SCHLUMBERGER ELECTRICAL LOG





Benjamin Franklin performed a famous experiment 200 years ago, which had a counterpart in the investigations of ground potentials carried on much later by the Schlumbergers. Franklin proved the existence of positive and negative electrical charges by flying a kite in a rainstorm.

This early experiment in the field of natural electrical potentials encouraged other investigators to start and continue work of increasing practical value. The measurement of ground potentials in bore holes by the Schlumbergers was one such important development. The resulting spontaneous potential curve was added to the already existing resistivity curve to complete the fundamental Electrical Log. The development, now only twenty years old, has had an increasing influence on oil exploration and production.

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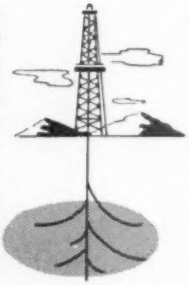

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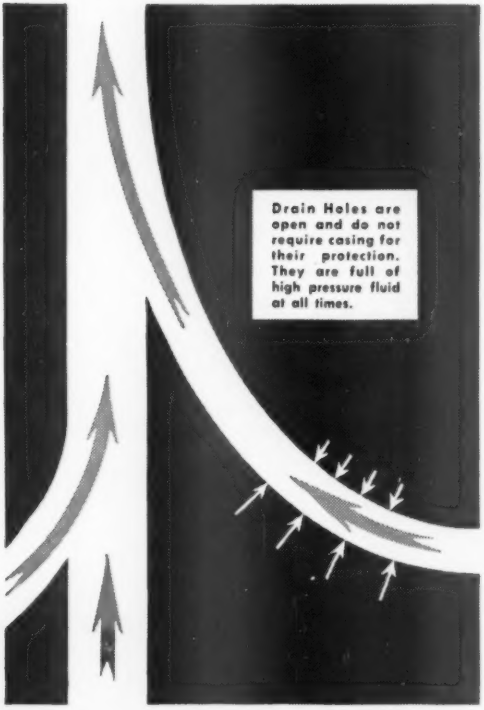

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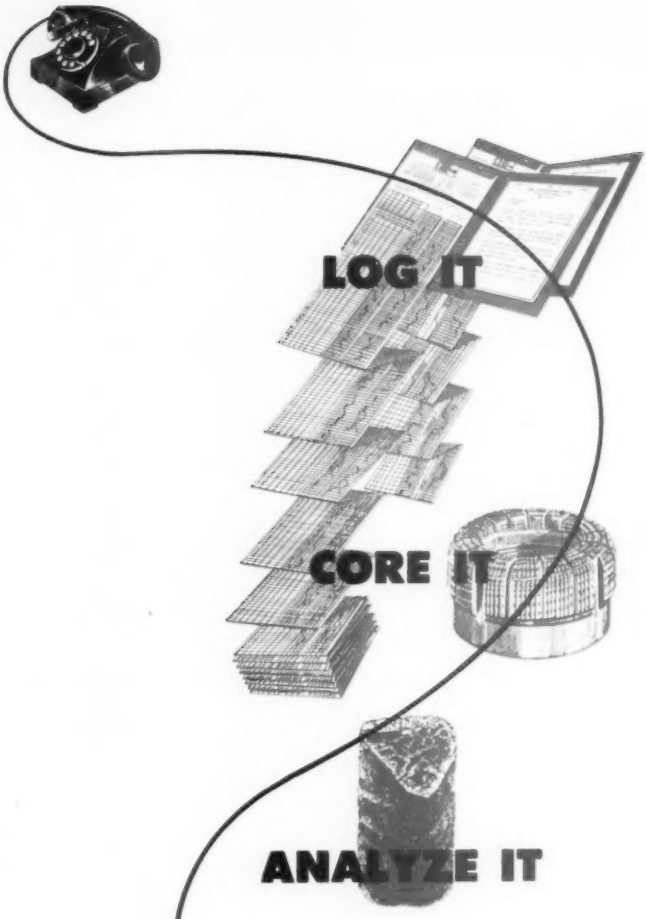

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THE PROFESSIONAL MAGAZINE FOR PETROLEUM ENGINEERS

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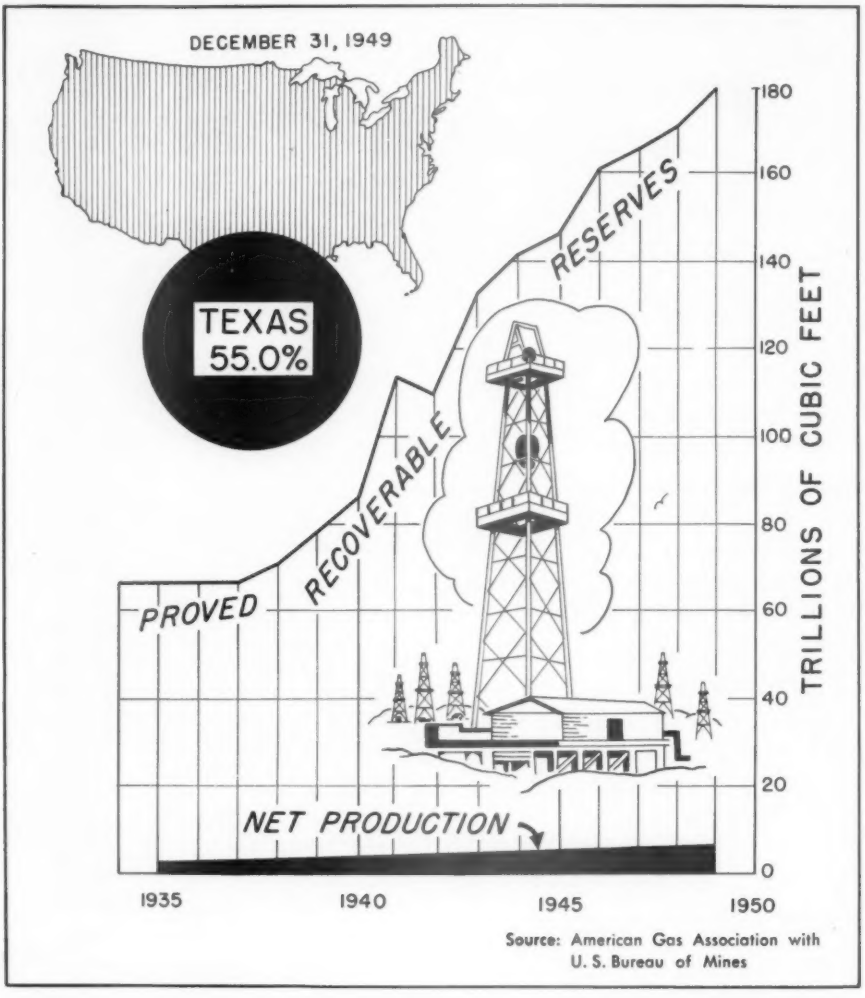
On the Cover — Relative permeability studies are conducted with this apparatus at California Research Corp.'s Oil Field Research Laboratory some 25 miles east of Los Angeles. Oil and gas flow simultaneously through cores and the flow resistance to each phase is being measured independently by Irving Fatt.

U. S. NATURAL GAS RESERVES



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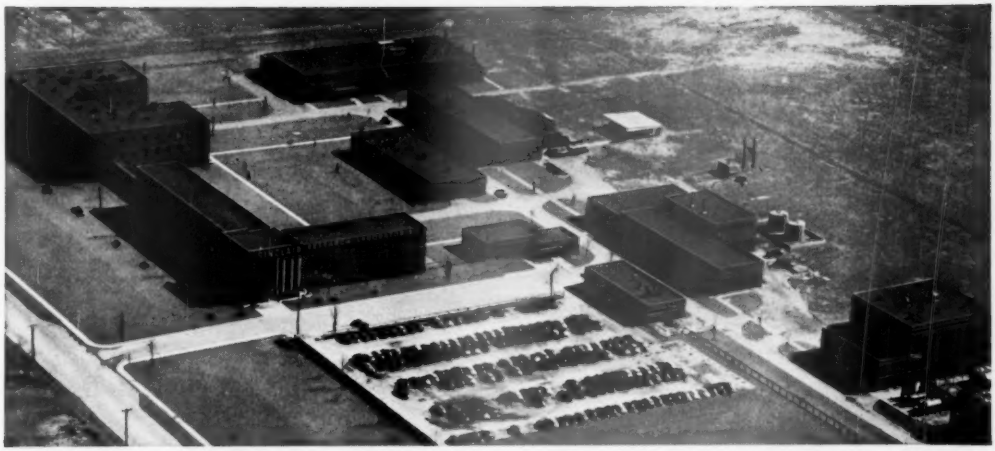

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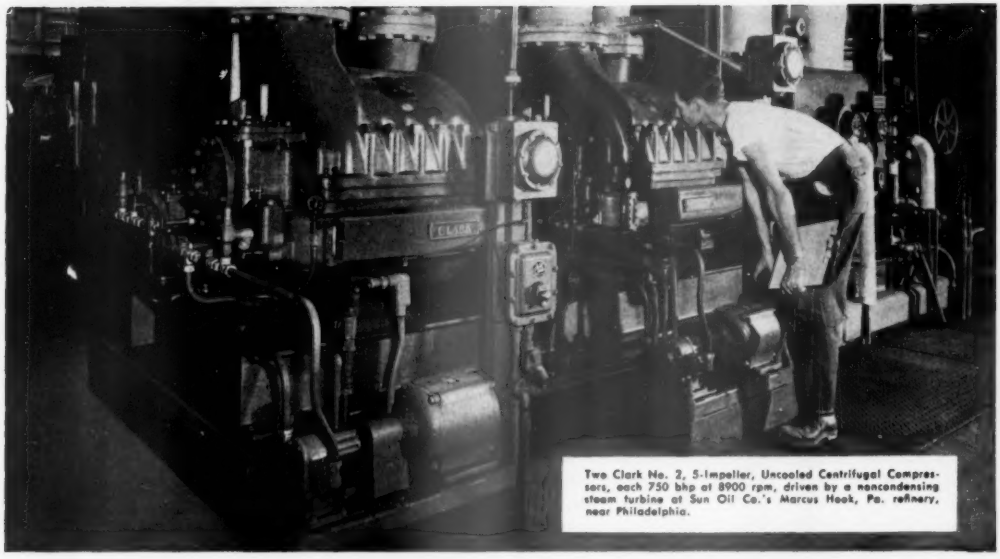

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In addition to conventional setting on tubing, the Baker Retainer Production Packer (Product No. 415-D) can be set on an electrical conductor cable by leading service organizations. See listing on opposite page of the organizations in your area, ready to give you prompt, resultful service.

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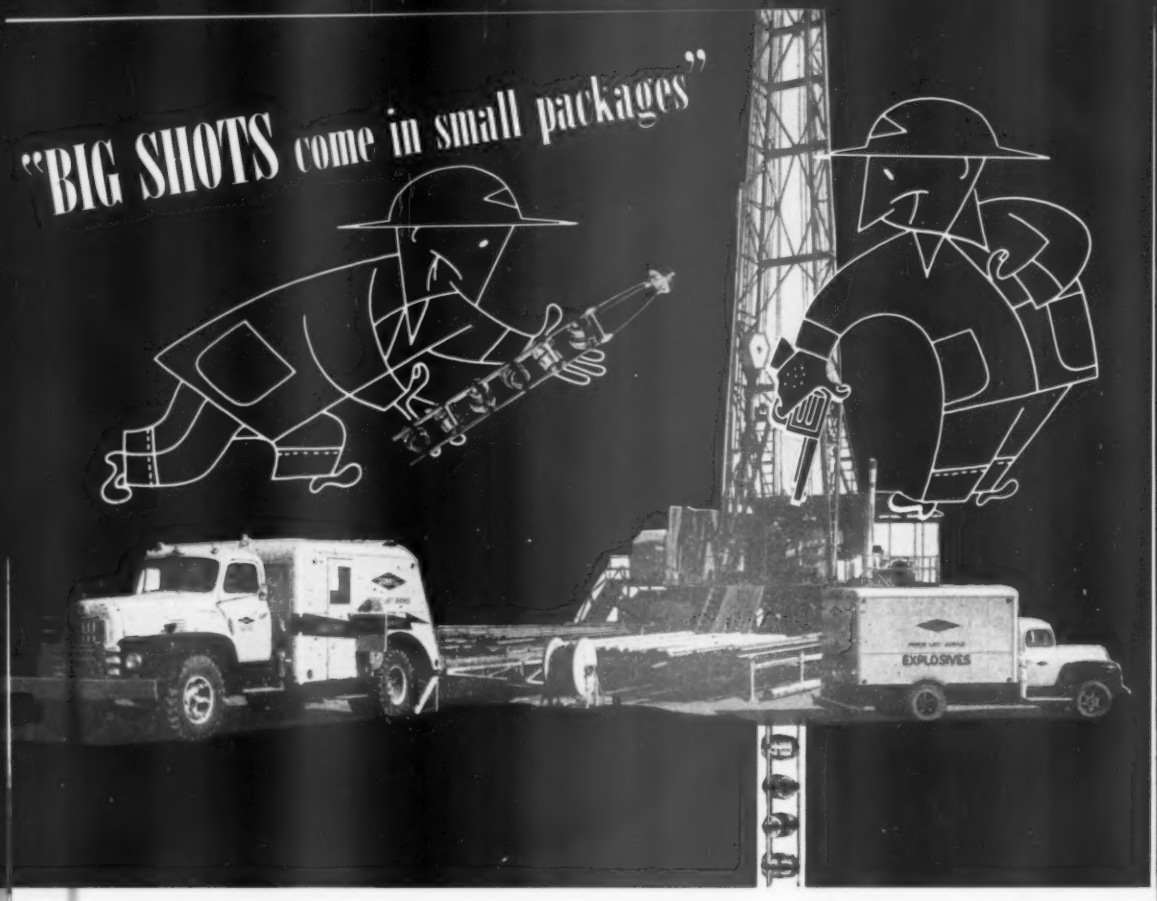
Baker Retainer Bridge Plug



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Offshore Production and Completion Practices — IN THE BAY MARCHAND AND MAIN PASS FIELDS

By J. L. LeBlanc
The California Co.

Offshore Problems Do Not End With the Exploratory Drilling Phase. Production and Transportation of Crude Oil From the Well Site Offers Additional Mountainous Problems. Changes in Completion Practices Must Be Effected in Some Cases. These and Additional Problems Are Discussed Here for Two Fields Off the New Orleans Coastline.

ABSTRACT

While the tremendous job of initiating exploratory drilling in the Gulf of Mexico was in progress, thought was also being given to the problems which might be encountered after production was discovered. Those working on these problems soon began to realize that the production and transportation of crude oil in the offshore areas offered as many difficulties as the drilling. As The California Co. discovered fields on the second and fourth offshore wildcats, production problems soon became reality. Concentration of drilling in these two fields, the Bay Marchand and the Main Pass Fields, accentuated production problems which seemed to have no possible economic solution. Fig. 1 indicates the general location of the two fields. The Bay Marchand Field is located approximately 65 miles south of New Orleans or about 3 miles offshore from the mouth of Bayou Lafourche, whereas the Main Pass Field is located approximately 75 miles southeast of New Orleans on the east side of the Mississippi River Delta and approximately 3 miles offshore.

In conjunction with the surface problems, subsurface problems began to arise from wells directionally drilled to shallow unconsolidated sands. Completion practices had to be changed to meet the new situation. A discussion of these subsurface problems and practices will be given in the latter part of the paper.

SURFACE PRODUCTION EQUIPMENT AND PRACTICES

Many schemes had been devised for the separation and transportation of offshore oil. All of these schemes seemed to be physically possible but few were even close to being economically practical.

Although these plans had been given careful consideration, nothing concrete had been agreed upon even up to the time the discovery well in the Main Pass Field was scheduled to be brought in. A temporary means of testing this well consisted of a separator installed on the drilling platform, a 65-bbl standby fresh water tank as a gauging tank and a barge moored alongside. These temporary installations served until drilling on the fourth well had begun. With the barge moored alongside, the drilling structure was continually being damaged. An anchoring system was devised for the barge, but this also proved impractical. Production subsequently discovered in the Bay Marchand Field was being handled in the same manner except with even greater difficulties. One can well imagine the hazards and difficulties encountered with such a production system in the Bay Marchand Field where 4 ft to 6 ft waves are common and 10 ft and 12 ft and even higher waves are not uncommon. We soon began to see that if production was to be placed on a daily basis a new system had to be inaugurated. Shallow producing horizons with their attendant sand problems further emphasized the necessity of abandoning the productive systems in use. Sufficient wells had been drilled or were in sight to justify economically the installation of 4-in. pipe lines to shore in both the Main Pass and Bay Marchand Fields. Pipe lines to shore based tankage and treating facilities had been judged the most economical and reliable. Accordingly, two 250-bbl tanks, separators and pumps were installed on the Main Pass "A" platform and a 4-in. pipe line was installed from this structure to a shore base where two 10,000-bbl tanks were erected. In the Bay Marchand Field flow lines were installed from the "B" and "C" structures to the "A" structure where two 250-bbl tanks, separators and pumps were erected and a 4-in. line connected these facilities to a shore base where four 10,000-bbl tanks were located.

These facilities soon proved to be well worth their installation costs. Hazards to field personnel were cut tremendously. Production was placed on a daily basis and allowable production was being made for the first time. These facilities continued to serve adequately and were thought to be sufficiently practical until the hurricane season of 1949. It was then realized that they embodied many drawbacks in addition to some uneconomical aspects already foreseen. When

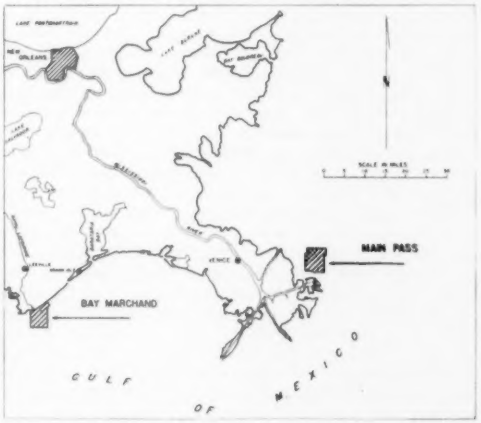
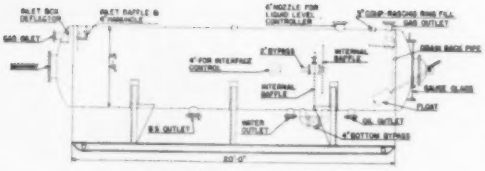


FIG. 1 — MAP SHOWING LOCATION OF BAY MARCHAND AND MAIN PASS FIELDS.

Paper presented at the Petroleum Branch Fall Meeting in New Orleans, La., Oct. 4-6, 1950.



5'-0" O.D. x 20'-0" LG.-125#

FIG. 2 — WATER KNOCKOUT SEPARATOR.

a hurricane originates in the Gulf of Mexico, waves build up to an alarming height in the Bay Marchand Field, even before the hurricane has been located. By the time hurricane notices are received the waves are of such height (15 ft and higher) that it is an impossibility to get personnel on and off the various production platforms. Wells must be left open with reliance being placed on flow line safety valves and tubing storm chokes, neither of which is effective. In addition to these features of insecurity, the system offered the possibility of becoming too cumbersome and requiring excessive operating manpower as development progressed.

It was agreed that a pipe line to shore was the best means of transportation but inasmuch as low tubing pressures and sanding conditions precluded the use of well energy it was necessary to have separating and pumping equipment offshore. Therefore work was started on the design of equipment which would meet all of the usual production requirements, in addition to being automatic to the extent that manpower could be reduced extensively. This work resulted in providing the systems now in use.

Fig. 2 provides a cross section view of the horizontal separator which is the piece of equipment around which all of the system is built. This separator is basically a pressure vessel 5 ft in diameter and 20 ft long, having a volume of approximately 70 bbl and constructed to withstand 125 psi operating pressure. In addition to being a separator, it acts as a surge tank, test tank and free water knockout. A complete production unit for a platform consists of two of these horizontal low pressure separators (one for bulk and one for test), two conventional horizontal high pressure separators, a pipe line pump, well head safety valves and necessary pneumatic controls.

Fig. 4 is a view of a complete unit in operation on the Bay Marchand "C" platform. One of the five producing wells on the platform is seen in the foreground. Each low pressure separator is equipped with two safety features: a high level controller which shuts in the wells in the event that the oil level in the separator rises above normal; and a high pressure controller which shuts in the wells in the event the pressure within the separator becomes too high. Each high pressure separator is equipped with a high level controller which shuts in the wells in the event the oil level in the separator becomes too high. High pressure controllers have not been installed on the high pressure separators because of the separator capacity to withstand well head pressures. Pilots on these controllers pneumatically activate piston operated Christmas tree safety valves which shut in the wells in the case of pump or other failures. The float on the low pressure separator operates controls which start and stop the pipe line pump at the appropriate time. Electrically driven pumps are used in the Bay Marchand Field where electrical power was made available through submarine cables. In the Main Pass Field, pumps are driven by pneumatically controlled internal combustion engines.

Periodic well tests can now be made with ease as the LP test separator has sufficient volume to permit 2 or 3-hour testing of wells. It is no longer necessary to provide gaugers and living quarters on each structure as was the case under the old systems. Two gaugers are now employed in each field whereas six would have been required under the old system. The cost of maintaining standby boats has also been reduced proportionally which makes a substantial reduction in daily operating costs. These automatic producing facilities have so far been practically trouble free, and their operation has been highly pleasing.

SUBSURFACE PRODUCTION AND COMPLETION PRACTICES

Bay Marchand Field

The Bay Marchand Field is situated on the largest known piercement type salt dome in the world. The salt has penetrated to very shallow depths, being contacted at 2,110 ft in the first well. All production to date been found in sands overlying the dome. No deep flank wells have been drilled as yet except on the northern flank which extends inshore and can be drilled by standard inland drilling barges. The northern flank has not been productive. Numerous tangential and radial faults complicate the subsurface geology. This in conjunction with slant holes makes the area a geologist's nightmare.

To date, six drilling platforms have been constructed in the field in an average water depth of 30 ft. From these platforms 27 wells have been completed as producers giving a total daily production of approximately 6,200 bbl. Production is from 13 different sands ranging in depth from 2,350 ft to 5,700 ft. The reservoirs being produced are of the water drive type with reservoir pressures being normal or near normal. The oil gravity ranges from 21° API to 41° API. Sixteen of the wells are producing by natural flow and four are producing by gas lift. Fourteen of the wells have been gravel packed to eliminate sanding troubles.

Two of the six platforms in the field were constructed so that two drilling rigs could be placed on the platform and both rigs could operate simultaneously. As all of the wells except one on each platform were drilled directionally, it was of major importance to plan development drilling carefully in order to prevent wells from running into each other. Fig. 3 indicates that even with careful planning two such situations came very close to arising on the "D" platform. Each circle on the sketch represents a vertical depth of approximately 100 ft. As the wells were drilled on 8 ft centers, every effort was made to keep the vertical sections of the hole straight.

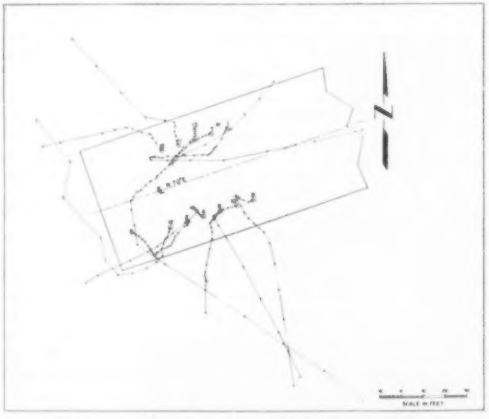


FIG. 3 — PLAN VIEW, "D" WELLS, BAY MARCHAND FIELD.

but as Fig. 3 shows the holes wandered considerably in spite of these efforts. Fig. 3 shows surface projections of the upper sections of the holes only as this is the only section where danger of collision existed.

Development in the Bay Marchand Field has been on an approximate 20-acre spacing program. Horizontal displacements of the wells have therefore averaged between 900 ft and 1,800 ft. If possible the wells are drilled at angles somewhere between 18° and 25° off vertical as this range is considered to be the best for directional control, but on occasions wells were drilled at angles of 30° and 35° off vertical and one one wildcat in the field an angle of 54° was reached without undue difficulty. The use of oil emulsion mud to reduce torque and drag in these directional holes has now become a standard practice. From 10 per cent to 15 per cent by volume of diesel oil is added to the mud. No particular effect has been noticed on sidewall samples and gas and water contacts are as readily established as they are in holes drilled without oil emulsion muds.

The unconsolidated nature of the shallow sands encountered in most cases demanded that some means of sand control be established during the completion programs. The use of gravel pack was considered the best means of sand control available for the conditions present in the Bay Marchand Field. Three types of gravel pack jobs have been employed in the field; (1) the single stage or inside casing pack, (2) the two stage pack inside casing where on the first stage gravel is squeezed out through the perforations and on the second stage the well is packed inside the casing, and (3) the open hole pack where a section of the casing is milled out, the hole underreamed and an open hole pack performed. All three types of jobs have proved successful from the standpoint of sand control but have varied widely from the standpoint of well productivity. Productivity indices have been established on all of the packed wells and vary from an average of .350 for the single stage packs to an average of 1.40 for the two stage packs and 4.3 for an open hole pack. This compares with an average PI of 6.0 for the unpacked wells in the field. From a productivity standpoint the open hole pack is definitely the best, but the costs of milling out casing and underreaming has until recently discouraged this approach when the other methods would suffice. Completions involving serious sand problems have until recently been standardized on the two stage pack, which is a compromise between cost and best results. However, three more open-hole packs, in addition to the above mentioned gravel packs, involving mill-out of casing and underreaming of sand have just been made with the anticipated good productivity and solution of sand problems and at a cost that, although high, is justifiable. The possibility of setting casing on top of a sand or the use of aluminum alloy casing for easier milling thus making open hole packs cheaper have both been given consideration, but the particular well features necessary for use of either procedures have not as yet been present.

One of the detrimental characteristics of a single stage pack is that it will gradually plug up, reducing flowing tubing pressures and production in proportion. This has been particularly true in the Bay Marchand Field where flowing tubing pressures, even though still reasonably high, are declining at a faster rate than anticipated. The one open hole pack performed in the field has as yet given no indication of declining flowing tubing pressures or production even though approximately 150,000 bbl have been produced from the well. This compares with the single stage packs where initial declines have usually been noted within the first 20,000 bbl of cumulative production. Most of the successful two stage jobs performed in this field and in the Main Pass Field have been

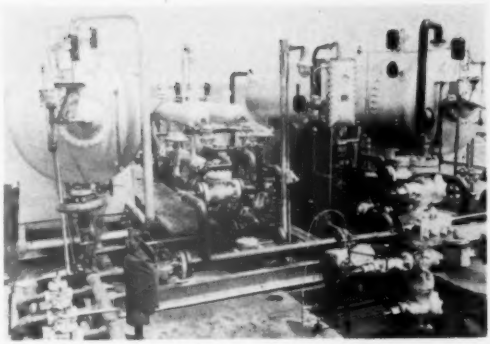


FIG. 4 — COMPLETE UNIT IN OPERATION, BAY MARCHAND "C" PLATFORM.

fairly recent, and no concrete information has been gathered as yet, although it is expected that these packs will have more favorable production histories than the single stage packs. A change in the size of gravel used has given no noticeable change in production characteristics. Gravel ranging in size from .060 to .090 in. was used on the first inside packs performed. This size is still being used on the first stage of the two stage packs but .040 x .060 in. gravel is now used inside the casing. The possibility of using even smaller gravel has been given consideration and will probably be tried in the future.

On several occasions diesel oil has been pumped down the tubing and through the gravel pack in an attempt to back wash the pack and thus eliminate the clogging effect. In general, if pumping pressures are not excessive, about 50 bbl of diesel are pumped through the pack and back into the formation. Results have not been phenomenal but have been satisfactory to the extent that the expenses involved are considered well worthwhile. On two occasions flowing tubing pressures have been restored to normal. The results no doubt would be much more satisfactory if selective washing could be done but this would require the use of a rig.

Main Pass Field

Subsurface production practices in the Main Pass Field have been substantially the same as those employed in the Bay Marchand Field and for that reason will not be discussed in detail. Three drilling platforms have been constructed in the field from which 11 wells have been drilled. Nine of these wells have been completed as producers in four sands ranging in depth from 5,500 to 8,150 ft. Daily production is approximately 3,000 bbl.

The field is situated on a deep-seated salt dome structure. All reservoirs being produced are of the water drive type with reservoir pressures and temperatures being normal. Faulting is general in the area but not to the extent found in the Bay Marchand Field.

Sand problems are present but have not in general been as prevalent as in the Bay Marchand Field. Three of the eight producers have been completed with gravel pack. Of these three packs two are of the single stage inside casing type and the third is the two stage type. Productivity indices of the packed wells are very similar to those found at Bay Marchand. Only a slight decline in tubing pressures of the packed wells has been noticed but these packs have been too recent to warrant any conclusions. Packing procedures have been identical to those used at Bay Marchand so no wide differences in results are expected. ★ ★ ★

Some Economic Aspects of the Oil Industry

A USC Student Chapter Report

Members of the Student Chapter at the University of Southern California met last month for their annual all-day meeting and heard, in addition to a brace of technical papers by graduates and undergraduates, a sharp criticism of the present Administration's economic policies. They were told that the achievement of any great financial success under present economic policies is "more or less impossible." Author of these criticisms was W. H. Geis, consultant, and banquet speaker for the occasion.

Earlier in the day, awards were made by the Pacific Petroleum Chapter and the AIME Petroleum Branch office in Dallas to first and second place winners in the graduate and undergraduate paper contest. In the graduate petroleum engineering division, Barry L. Evans took first place and George Tchillingarian took second place. In the undergraduate division, R. C. Kirchman was awarded first place. The Pacific Petroleum Chapter gave all winners a slide rule and the Branch rewarded first place winners with copies of *Subsurface Geologic Methods*. Chairman of the Awards Committee was Paul Andrews of Signal Oil and Gas Co.

At the evening banquet, Geis glumly warned the young engineers that they "probably will suffer the greatest frustrations if the present controlled economy, which in fact is a form of economic socialism, continues." He compared the economic programs of Socialistic England and the United States in this manner:

So far England has nationalized, or rather expropriated from private enterprise, the coal, steel, railroad, banking, and some other industries, including the general direction of labor as a form of industry. That means that the English government receives all the net revenue or the net profits from 50 per cent of its industries. This year in the United States the government, through the operation of the federal income tax laws, will receive not less than 55 per cent, and in some cases as much as 77 per cent, of the net revenue, that is, the net profit, from 100 per cent of the United States' industries. In comparative terms, while 50 per cent of English industry works 100 per cent of the time for England, 100 per cent of American industry works 55 per cent, or 77 per cent, of the time for the American government. Under such a comparison, which government has turned further towards socialism?

In addition, another avowed purpose of the socialists and communists is to destroy private capital. Mexico, at least, made no bones about it. Mexico simply expropriated all the properties and assets of the oil companies and so did Red China with British Asiatic Oil Co. These were direct and positive actions. But the more favored way to destroy capital is by the slower, but just as sure, method of levying a tax on capital. It is a well known economic principle that whenever capital, as such, is taxed it must eventually follow that the capital is destroyed.

In this regard Britain is smart, for with all of its advertised socialistic trends it has never yet levied a tax on capital or on capital gains; nor has it ever levied a tax on dividends, which are a reward for the use of capital by industry.

On the other hand, the United States, by indirection and by various devious means, levies a tax on 85 per cent of the capital in the mining industry and on 72½ per cent of the capital of the oil industry. The government does this contrary to basic, sound economic principles, simply by classifying the return of capital as ordinary income. As a result, the independent mining industry which flourished so well in its early history is practically non-existent in the United States today because its capital is gone and investors will not risk capital against such odds. It is, of course, true that a very few powerful mining companies remain which, largely because of their size, have been able to revive their capital through outside investments. In addition, an income tax is levied against all dividends in the United States, and the Treasury Department has now asked Congress to

Continued on Page 2, Section 2

USC STUDENT PROGRAM — Student paper contests held last month at the University of Southern California produced three winners in the petroleum engineering division. Shown above are, L to R, Barry L. Evans, first place winner in the graduate class; R. C. Kirchman, first place winner in the undergraduate class; Paul Andrews of Signal Oil and Gas Co., Awards Committee chairman; W. H. Geis, banquet speaker; and George Tchillingarian, second place winner in the graduate class.

History and Development of the AAODC Training Programs

Reported by Brad Mills
Permian Basin Section

The most pressing need in the drilling industry today is for trained personnel, believes A. W. Thompson of Thompson-Carr, Inc., Houston, president of the American Association of Oilwell Drilling Contractors. Thompson outlined the development of the AAODC training programs before a meeting of the Permian Basin Section May 21.

Training is reflected, Thompson said, in ways other than the technological end of the work. There is also developed an improved morale and attitude, greater teamwork among the men and an intangible quality of workmanship that leads to more and better footage of hole per dollar spent. Thompson attributes the increase in drilling efficiency in recent years partly to the association's research and educational programs, all of which were begun in the Permian Basin area.

Drill pipe corrosion was the first problem to be approached by the contractors. Battelle Memorial Institute, Columbus, Ohio, was selected to conduct a program of research, which was financed by individual subscription of contractors. A Research Committee of AAODC was appointed to work with Battelle, and the program was initiated in July, 1945.

One of the conclusions of the studies was that corrosion of drill pipe was closely related to the muds used. In September, 1945, John Woodruff, State Coordinator of Petroleum Industry Training at the University of Texas, proposed to the association a mud research and mud training program in collaboration with the University. This program went into effect in February, 1946, and in April of that year the association made a grant of $6,000 to the University of Texas for expansion of the program.

Later in the year the first Research and Education Committee was formed. With the increase of deep drilling, industry began to feel the need for trained men more acutely. In order to give basic training to young men entering the business as drillers and toolpushers, a Drilling Practices Course was organized in February, 1947. The first course was set up at Kilgore College in cooperation with the University of Texas. A complete drilling rig was donated for this work by various drilling contractors and supply firms. During that year the present programs were expanded to include further grants to the University of Texas and additional Drilling Mud Control Schools in various parts of the country.

Two new training programs were organized in 1948. A supervisory program, "Accident Prevention Through Better Supervision," was established on a conference basis, and conferences were held in Texas, Wyoming and Oklahoma during that year. A series of Management Institutes was organized to begin in 1949, covering functions of management, personnel problems, accident prevention, cost factors, security for the drilling organization and legal problems of the drilling contractor. A Drilling Engines course was also planned.

RUPERT C. CRAZE, research specialist for Humble Oil and Refining Co., spoke on "The Performance of Limestone Reservoirs" before the monthly meeting of the Gulf Coast Section June 18. He discussed the fundamental principles governing oil and gas production from sandstone and limestone, and the application of analytical techniques used for sandstone reservoir studies to the study of limestone reservoir performance.

The first Management Institutes in 1949 had an advance registration of nearly 500 men. The Mud Schools and the Supervisory Training Programs were continued at the same time. Assistance from several insurance companies was secured for the Supervisory Training Programs. Supply and manufacturing companies donated a complete engines laboratory for the first Drilling Engines Course, organized in September, 1949. A new Educational Administrative Committee had been appointed by this time to coordinate the expanded programs and supervise expenditures.

During 1950, efforts were made to expand the Employer Unit Plan of Supervisory Training, which had been started in the Permian Basin with the Carl B. King and W. H. Black Drilling Companies. Management Institutes were held in 11 different drilling centers for 215 persons. Topics for this second series, selected from a poll taken at the first institutes, were contractor-company relationships and insurance problems.

During 1951 the Mud Schools have been expanded, the Supervisory Training Program has been enlarged to include California and the Rocky Mountains, and Oklahoma units have increased. The Gulf Coast unit has been added. A new course to supplement the Employer Unit Plan is known as Field Institutes. It is a specialized training aimed at toolpushers and drilling superintendents, providing conferences on specific drilling problems. A new project is underway to publish an illustrated booklet on oilwell drilling terminology, written primarily for office personnel in drilling and oil companies.

Currently, Mud Schools have been held in Kansas, Casper, Wyo., and West Texas; Field Institutes are being held once a month in the Permian Basin and in Casper; and Employer Units are operating in the Permian Basin, Gulf Coast, Oklahoma, California and the Rocky Mountain areas. ★ ★ ★

Predicting Reservoir Performance — II

Reported by John Clayton Jacobs, Jr.

North Texas Study Group

The two final Spring meetings of the study group of the North Texas Section were held on May 9 and May 23, led by A. B. Dyes of the Research and Development Department of the Atlantic Refining Co. These two discussions dealt with the application of material balances to the prediction of reservoir performance. Primarily emphasized was the means of evaluating the magnitude of a reservoir water drive and the manner in which flash and differential P-V data are employed in material balances.

In developing the optimum method of producing an oil or gas reservoir, the magnitude of any water drive which may be present and its effectiveness in the future must be known. The water drive at any given date can be evaluated by material balance if the quantity of in place material, production and pressure histories, and fluid properties are accurately known. However, since the volumetric estimate of in place material is only approximate, the definition of the water drive by this means, if done early in the life of a field, will be inaccurate and can lead to large errors in the prediction of the future effectiveness of the water drive. The use of many material balances employing several different degrees of water drive with several values of in place material to define the pressure decline will permit the selection of the in place material and water drive to yield a minimum deviation of the calculated pressure decline from that observed in the field. These quantities can then be used in calculating the future behavior of the reservoir.

The future water drive cannot be obtained accurately by an extrapolation of the coefficient in the Schilthuis or "short form" Hurst equation except under very special reservoir conditions. These conditions are not generally present until late in the producing life of the reservoir. In predicting the amount of water influx with time, either the electric analyzer or the "long form" calculation procedure developed by Hurst should be employed to give the most reliable results.

In predicting the performance of a reservoir, utilizing material balances, the P-V properties of the reservoir fluids must be known. These are described by two types of P-V data, one obtained by differential liberation of gas from the reservoir fluid over small pressure changes at reservoir temperature and the other by flash liberation of gas from the reservoir fluid by one reduction in pressure to the separator pressure and temperature as present in the field. Both differential and flash data must be employed in making material balance studies. The stock tank oil and separator gas production as reported from the field should be converted from flash to differential production and employed in a material balance using differential P-V data to describe the performance in the reservoir. Likewise, predictions in the future would be obtained from material balances employing differential data by converting the predicted differential production from the reservoir to flash production in the stock tank. The use of only one type of P-V data can lead to appreciable errors in the estimation of in place material and reservoir performance. ★ ★ ★

Making Research Results Useful

Reported by Herman Dykstra

Pacific Technology Group

The fourth lecture of the present series on research being conducted by the Pacific Technology Group was given by Howard C. Pyle, petroleum engineer, on May 28, at the General Petroleum Auditorium in Los Angeles.

Pyle began by defining research according to Webster and by classifying research as pure basic, or long term, research and industrial, or short term, research. Long term research is mainly concerned with the investigation of fundamentals, whereas short term research is mainly concerned with answering specific problems as are often found in industry. An example of a long term research is API Project 37, "Fundamentals of Hydrocarbon Behavior." Industry does not usually take such a research project because the application of results is not immediately apparent.

As an example of short term research Pyle described the development of mud scratchers. Someone suggested the use of a mud scratcher and accordingly research was carried out to determine the effectiveness of a mud scratcher. Within a few weeks results were obtained which showed that mud scratchers were feasible.

Actually many research projects are both long term and short term projects. Useful results are obtained during the research work but, nevertheless, the project is extended for years.

All research eventually pays off and has a useful objective. Research is financed by industry, and employers want results and facts, and many times may want to expand on the basis of results already obtained.

Pyle concluded by giving several rules that he believed researchers should follow in order to get maximum usefulness from research results.

1. Researchers should be enthusiastic about their work and should keep their research objectives foremost in their conversation. They should avoid the temptation of talking about interesting phases of their research that are not directly related to the objectives.

2. Researchers should speak in simple terms easily understood by management and those who hold the purse strings.

3. Researchers should appreciate economics of research and should know the cost of carrying on research. On the other hand management should not measure all research in terms of dollars and cents.

4. Research reports should be written for the non-researcher in simple straightforward language. Technical supporting results should be placed in an appendix. This includes all differential and integral signs.

5. Use of graphs and illustrations are helpful to bring out facts and figures.

6. The researcher should keep management informed of results.

7. Research men should be prompt in presenting their ideas and results of their work. Research is big business and should be handled as such. ★ ★ ★

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THE QUANTITATIVE APPLICATION OF RADIOACTIVITY LOGS

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ABSTRACT

The object of this paper is to report recent developments in the quantitative interpretation of radioactivity logs. The use of reference lines is described in the application of the new zero radioactivity reference line for the determination of neutron derived porosities is discussed. Illustrated examples are shown of logs from the reef limestone of the North Snyder Field and from the Lansing-Kansas City limestone of central Kansas.

A method of using an interrelation factor calculated from the neutron and gamma ray curves, called the neutron productivity number, for the estimation of productivity from sandstone formations is discussed. When used in a relative manner the neutron productivity number has aided in predicting whether a given zone will produce gas or liquid or whether it is too shaly to produce. Examples of logs from wells in the Freites District, Venezuela, and in East Texas are shown to illustrate the application of the neutron productivity number.

INTRODUCTION

The petroleum industry was introduced to some of the preliminary results of investigations into the quantitative interpretation of radioactivity logs in October, 1949.[2] It was stated at that time that the methods presented were entirely relative because they involved the use of reference points obtained from the radioactivity log, *i.e.*, shale reference lines, dense zone reference lines, or a combination of both shale and dense zone reference lines. These relative methods offered many advantages to the industry in interpreting radioactivity logs in terms of porosity with particular application to limestone and dolomite reservoirs. However, these relative methods did not offer the wide range of applicability desired because the establishment of reliable reference points from shale in some areas were difficult. It was recognized that a more reliable means of establishing reference lines was vitally needed. Such a method is now available through the introduction of an instrumental zero device. It is the purpose of this paper to discuss the application of this new zero reference to the quantitative interpretation of radioactivity logs.

Previously all applications of quantitative interpretations of radioactivity logs have been made in limestone reservoirs with little or no emphasis placed on sandstone reservoirs. A brief resumé of investigations into the quantitative interpretation of radioactivity logs in sandstone reservoirs is presented here. This discussion deals primarily with the interrelation of the gamma ray and neutron curves and the response of the latter to the density of the fluids filling the pore space in relatively homogeneous sandstones of uniform porosity. The authors believe that the methods presented herein are only applicable locally to specific fields and reservoirs, and that they probably do not offer a wide range of applicability.

However, the authors believe that the wider use of the new instrumental zero references in sand areas will reveal more information about the specific response of the gamma ray and neutron curves to changes in lithology and saturation.

Two applications of quantitative interpretation using the new instrumental zero references are presented. Examples are given which show the comparison of logs and porosity in the limestones and dolomites of West Texas and Kansas. Logs of wells in Venezuela and East Texas are compared with the drill stem test data, production data, etc., to illustrate the interrelation of the gamma ray and neutron curves and the use of methods involving these interrelations to determine certain saturation variables.

THE QUANTITATIVE APPLICATION OF RADIOACTIVITY LOGS TO LIMESTONE AND DOLOMITE RESERVOIRS

The theoretical basis for the gamma ray and neutron curves has been discussed elsewhere.[3] The method of recording the logs and apparatus involved has also been thoroughly covered and will not be discussed here.[1,2,3,4,9]

It has been shown that the neutron curve responds exponentially to liquid filled porosity over the 1½ to 35 per cent

[1]References given at end of paper.
Manuscript received in the office of the Petroleum Branch Sept. 8, 1950. Paper presented at the Fall Meeting of the Petroleum Branch in New Orleans, La., Oct. 4-6, 1950.

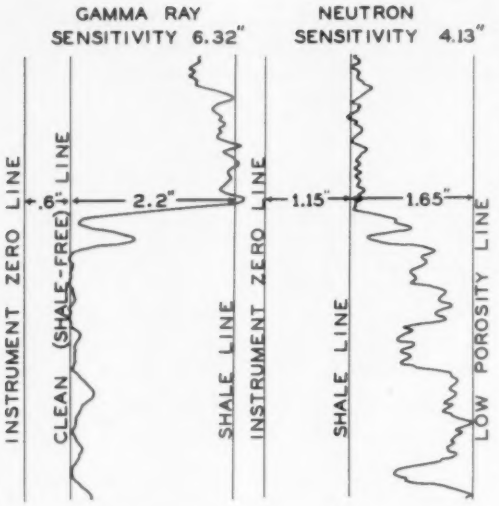

FIG. 1 — RELATIONSHIP BETWEEN RELATIVE REFERENCE LINES AND THE ZERO RADIOACTIVITY REFERENCE LINES FOR 7" CASED HOLE.

range in limestones and dolomites.[5] It is assumed therefore that the relationship between the neutron curve deflections and porosity for a given zone, can be determined graphically by using this relationship to weight the average line drawn through a plot of the scattered values of the neutron curve deflections and the corresponding porosities.

Introduction of Instrumental Zero Reference Lines

Previous work has made use of relative methods in which reference lines were established from the shale line of the neutron curve. However, shale lines were not always easily established and it was therefore quite apparent that some method of obtaining a better zero reference was needed. A zero locating device has now been added to the existing logging equipment. It is now possible to determine the position of zero radioactivity on the log at any time during the logging operation. Fig. 1 shows the relationship between the instrument zero and the shale reference lines for the gamma ray and neutron curves in a typical limestone area. To acquire more adequate control of the sensitivity, a sensitivity selector is now available which permits accurate measurements of the sensitivity and the setting of any desired sensitivity. The addition of this equipment makes it possible to standardize sensitivities for given logging conditions; *i.e.*, under given casing and core hole sizes.

To illustrate the application of quantitative methods to limestone reservoirs, a well in the reef limestone of the North Snyder Field, Scurry County, Tex., was chosen because core data were available within the same well for both cased hole and open hole conditions. Fig. 2 shows the correlation of the radioactivity log and the core porosity log of a standard Oil Co. of Texas well in the North Snyder Field.

Preparation of the Radioactivity Log For Quantitative Interpretation

To prepare the radioactivity log for quantitative interpretation the location of the absolute zero reference line is determined at one or more points within the zone of interest and throughout the remainder of the log on both the gamma ray and neutron curves. The porosity determined by core analysis is then plotted on the same vertical scale as the radioactivity log and correlated core by core with the neutron curve. Where physical bore hole conditions such as casing or bit size are changed within a well it is necessary to prepare a separate quantitative interpretation chart for each section of the well. A data sheet showing the depth, the gamma ray curve deflection from zero, the neutron curve deflection from zero, and the porosity of the corresponding core sample is then prepared, throughout the cored section, until all of the data necessary to prepare the neutron derived porosity curve are recorded.

Neutron Derived Porosity Curve

By assuming that the neutron curve responds in an exponential manner to liquid filled porosity, the establishment of the neutron derived porosity curve is facilitated if the data are plotted on semi-log graph paper with the neutron curve deflection as the abscissa (linear scale) and the per cent core porosity as the ordinate (log scale). The neutron derived porosity curve is determined by drawing the straight line that best fits the scattered points. When the neutron curve deflections are plotted in units of distance of pen travel (inches) it is necessary to adjust for changes of sensitivity when applying the data of one log to that of another log. The relationship of the sensitivity to the deflection is linear and therefore the neutron derived porosity curve may be adjusted to another sensitivity by multiplying it by the ratio of the new to the old sensitivity.

However, if the neutron curve deflection is divided by its sensitivity, an invariant quantity is obtained which is applicable to any log. This quantity has been called a standard unit, and the neutron derived porosity curve may be plotted in either standard units or inches of deflection as desired. Figs. 2 and 3 show an example of the use of standard units, while an example of a neutron derived porosity curve plotted in inches of deflection is shown by Figs. 5 and 6. The value in standard units for any neutron curve deflection may be found by dividing the curve deflection (in inches) at the given point by the sensitivity of the curve.

The neutron derived porosity curve shown in Fig. 3 represents data obtained from that portion of the cored section which had been cased with 7-in. pipe (Fig. 2). This curve may be applied to any other well in the area in which 7-in. casing is set and on which an absolute zero reference line was obtained.

This curve (Fig. 3), with its relatively small scattering, is typical of the reef limestones in this region and has been found to be applicable over wide areas of West Texas.

The same procedure was followed for the 6¼ in. open hole condition. The gamma ray and neutron curve deflections from zero were determined opposite each of the corresponding core porosities, and each deflection divided by its respective log sensitivity, thus converting to standard units. The neutron standard units opposite clean limestone (as shown by the gamma ray curve) were then plotted as the asbscissa (linear scale) versus the per cent porosity as the ordinate (log scale) on semi-log graph paper and the average neutron derived porosity curve established by drawing a straight line through

these points. Fig. 4 shows the neutron derived porosity curve for 6¼ in. open hole. This curve may also be applied to any well in this area with 6¼ in. open hole on which a radioactivity reference line was obtained.

Comparison of Lansing - Kansas City Logs and Porosities

Fig. 5 compares the logs and core porosity data for a well producing from the Lansing - Kansas City section, Stafford County, Kans.

In addition, this example illustrates the application of a method of averaging the core porosities in order that the lengths of the core samples will agree more closely with the length of the sample affecting the neutron curve. The length of the neutron curve sample is approximately two ft while the core porosities were obtained from permeability plugs which were selected as representative of one-ft intervals of the core. This difference in length will result in a greater degree of scattering of the points used in determining the neutron derived porosity curve. The neutron curve subsurface instrument is not influenced to the same degree by each longitudinal unit of the interval sampled, as the middle portion of the sample (of approximately one ft of its total length) exerts the greatest influence while in the remainder of the sample (over the six in. at the ends) the influence of the sample on the neutron curve decreases to zero. The determination of the weighting factors would be too complicated to perform for a practical example and therefore a rough approximation was resorted too. This has been done by averaging the porosities for three one-ft intervals of core so that the middle foot of core is weighted at full value while the foot below and the foot above is weighted by one-half; that is, the porosity of the middle portion is taken at full value, one-half the value of the porosities of the adjacent intervals is added and their sum is divided by two. The result is shown in Fig. 5 in the column labeled "Per Cent Weighted Porosity." It will be noted that much better agreement exists between these values and the neutron curve than exists between the unweighted porosity values and the curve.

The neutron derived porosity curve for the Lansing - Kansas City well is shown in Fig. 6. Here the neutron curve deflections are plotted in inches.

To apply this neutron derived porosity curve to logs of other wells having the same physical bore hole conditions it is necessary to apply a correction if the log was run on a different sensitivity. This correction may best be made by selecting two points on the base neutron derived porosity curve, on even porosity lines, *i.e.*, two per cent porosity and 20 per cent porosity. The neutron curve deflection in inches is determined for each of these points and each is multiplied by the ratio of the sensitivity of the new log to that of the old log, in order to obtain the correct deflection to be plotted along the corresponding porosity line. These points are then connected by a straight line, giving the corrected neutron derived porosity curve, which may then be applied to the neutron curve being considered.

Application to Logs for Which No Instrumental Zero Is Available

The neutron derived porosity curve established from a given log may be applied to another log having only a shale reference line, by determining the location of the shale reference line in relation to the absolute zero reference line on the base log, and measuring this distance in inches, which figure is divided by the sensitivity of the base log to obtain the distance from shale to zero in terms of standard units. The location of zero may be placed on the new log by multiplying the sensitivity of the log by the number of standard units obtained and positioning the zero this distance to the left of the shale reference line (Fig. 1). The neutron derived porosity curve determined from the base log may then be applied as if the absolute zero were known. The accuracy of this method of

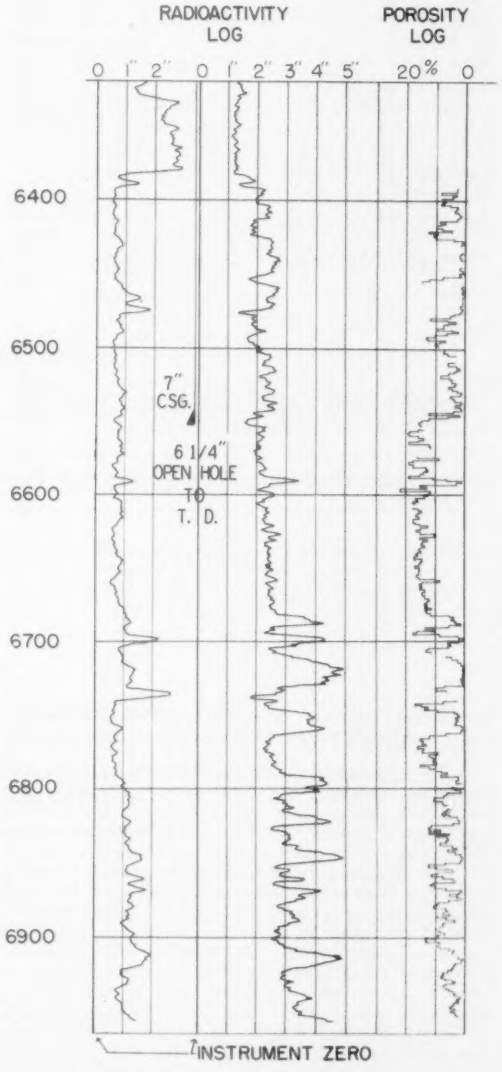

FIG. 2 — COMPARISON OF THE RADIOACTIVITY LOG AND CORE POROSITIES IN KELLY-SNYDER FIELD, TEXAS.

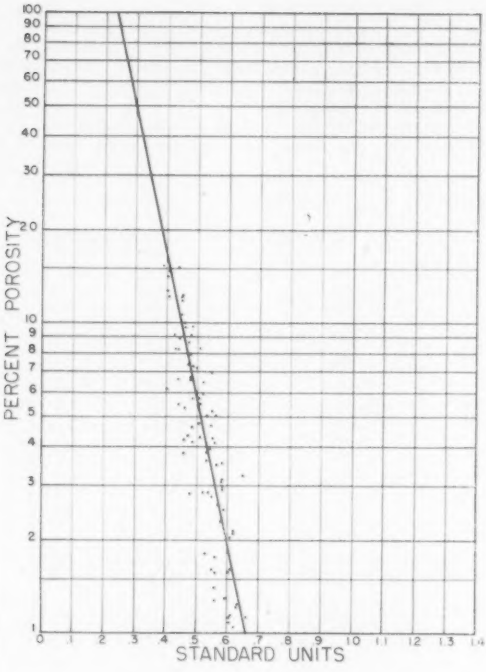

FIG. 3 — NEUTRON DERIVED POROSITY CURVE FOR 7" CASED HOLE, KELLY-SNYDER FIELD.

establishing absolute zero is dependent upon the constancy with which the average shale line is established from well to well and the accuracy of the response of the neutron curve.

APPLICATION OF QUANTITATIVE METHODS OF INTERPRETATION TO SAND FORMATIONS

It has been known for some time that the gamma ray curve can be used to estimate the relative shale content of the sand and for this purpose a linear relationship may be assumed to exist between the deflection of the gamma ray curve and the shale content of the sand. The gamma ray curve is affected solely by the gamma radiation emitted by naturally occurring radioactive elements distributed among certain of the rocks composing the earth's crust. In some rocks the radioactive elements are present in a very constant concentration. The radioactive content of shale, for example, is often sufficiently constant in a given production zone that the percentage of shale at a given depth may be estimated by comparing the gamma ray curve deflection at the given depth with the gamma ray curve deflection at a point opposite pure shale. The neutron curve, on the other hand, responds to lithology in a much more complicated manner. This curve reflects lithologic conditions in terms of the effect produced on the neutrons emitted from the source by the hydrogen content of the rock, the cross sections for the scattering and capturing of neutrons of the elements composing the rock, and the atomic density of these elements in the rock.

In clean (silt and shale-free) limestone or dolomite formations the effects of the hydrogen content and that of the cross section for neutron capture act in combination to shift the neutron curve to the left. The scattering cross section and density effects also act in combination and shift the curve to the right.[9] In the simple case where the neutron curve deflections opposite mixtures of dolomite or limestone and liquid hydrocarbons or water were studied, it was found that a simple exponential relation exists.[9] However, this simple relationship will not apply to most sandstones because of their more heterogeneous chemical composition and the resulting more complex effect on the neutron curve. All of the requirements for calculating a neutron derived porosity for sandstones from the neutron curve are not known, but in addition to the three factors previously enumerated there may be factors which depend on the chemical composition of the matrix and cementing material. Because these factors are still unknown, the neutron curve has not, as yet, been used to determine porosity in sandstones.

However, it has been found that in certain cases the neutron and gamma ray curves can be used in combination to assist in estimating the productivity of a sand section; *i.e.*, whether the section is too shaly to produce or whether it will produce gas or liquid. This use depends upon the reliability of the

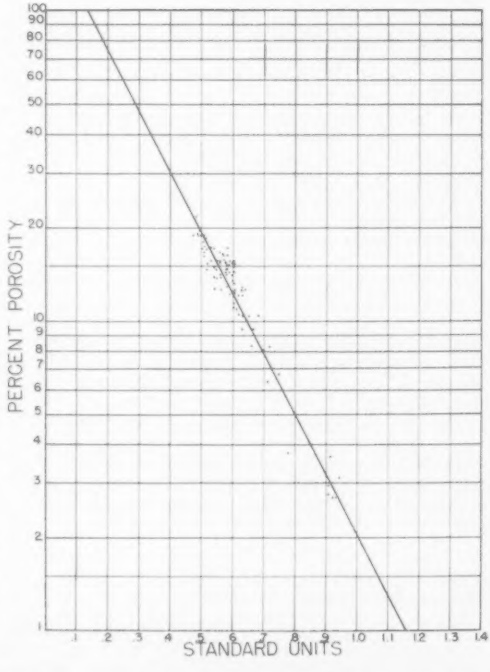

FIG. 4 — NEUTRON DERIVED POROSITY CURVE FOR 6¼" OPEN HOLE, KELLY-SNYDER FIELD.

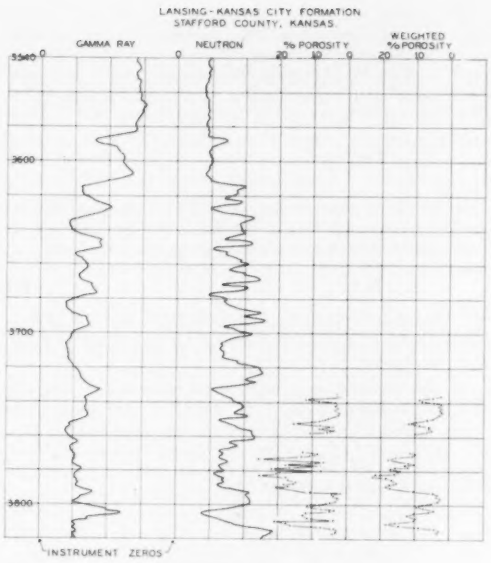

FIG. 5 — COMPARISON OF THE RADIOACTIVITY LOG AND CORE POROSITIES IN STAFFORD COUNTY, KANSAS.

gamma ray curve for estimating the amount of shale present and the application of this curve in a compensatory manner to the neutron curve. Shale contains large proportions of chemically bound water and hydrocarbons; and therefore the neutron curve is affected by shale in a similar manner to that produced by its constituent substances when in the free liquid state. The gamma ray curve may be used to calculate a factor which has a compensatory effect for shale on the neutron curve deflections, and with its aid it is sometimes possible to estimate the productivity of shaly sands from the neutron curve. This factor has been called the gamma ray shale factor.

Calculation of the Gamma Ray Shale Factor (G_s)

The gamma ray shale factor is an empirically derived function of the per cent total gamma ray curve deflection. The total gamma ray curve deflection is the distance between the deflection values for clean, silt-free, shale-free sandstones and the deflection values for the pure shale. The per cent total gamma ray curve deflection is obtained by dividing observed gamma ray curve deflection at a given depth by the total gamma ray curve deflection and multiplying by 100. G_s is expressed as a logarithmic function of the total gamma ray curve deflection (D_g) as follows:

$$G_s = 1 + \log\,[1 + \log\,(D_g + 1)] \quad . \quad . \quad . \quad . \quad (1)$$

G_s varies from 1 to 1.477 as D_g varies from 0 to 100. A plot of the values of G_s versus the values of $(D_g + 1)$ are shown in Fig. 7.

Application of Gamma Ray Shale Factor To Sand Formations

A relative method using an interrelation factor calculated from the per cent total neutron curve deflections and the gamma ray shale number has been developed, making it possible to predict the productivity of a zone within certain limitations. This interrelation factor has been called the neutron productivity number (N_p). Using a method based on the use of the neutron productivity number, it has been possible to determine the type of production to be obtained from the zone in question in many instances.

The neutron productivity number (N_p) is determined in the following manner:

$$N_p = G_s(D_n + 1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where:

D_n is the per cent total deflection for the neutron curve and G_s is the gamma ray shale factor, or:

$$N_p = (D_n + 1)\,[1 + \log[1 + \log(D_g + 1)]] \quad . \quad . \quad (3)$$

The neutron productivity number should be used only in a relative manner by comparing the productivity numbers calculated from the curves of a well whose productivity is to be estimated, with the values of productivity numbers for wells producing from the same section. To establish neutron productivity numbers for producing sections of a field, drill stem tests and production tests diagnostic for individual sections

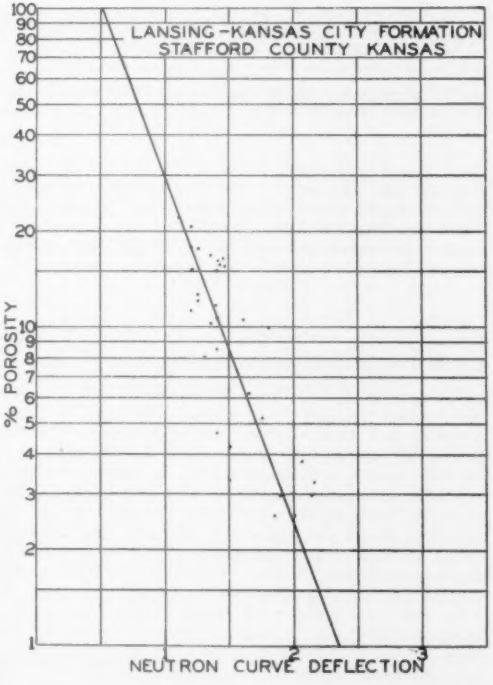

FIG. 6 — NEUTRON DERIVED POROSITY CURVE FOR 4½" CASED HOLE, STAFFORD COUNTY, KANSAS.

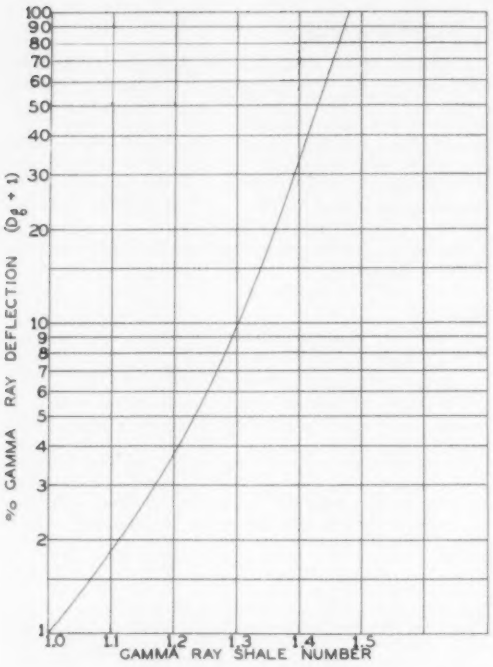

FIG. 7 — RELATIONSHIP BETWEEN GAMMA RAY SHALE NUMBER AND GAMMA RAY CURVE DEFLECTION.

must be compared with the productivity numbers calculated from the logs. The neutron productivity numbers calculated from the log of a well whose productivity is unknown, but which penetrates the same sections can be compared to the neutron productivity numbers for the known wells and an estimate made of the probable production to be expected.

Calculation of the Neutron Productivity Number

The variables D_g and D_n are determined from their respective curves as follows. First, average shale lines are determined for each curve, which are labeled "100" and "0" on the gamma ray curve and the neutron curve, respectively. A typical clean section is then selected on the gamma ray curve and a line is drawn through these deflections parallel to the shale line previously drawn. This line is labeled "0" and the deflection between the line marked "0" and "100" is known as the "total gamma ray curve deflection." (D_{gt}). A line is drawn through the deflections of the neutron curve opposite a clean zone known to be producing liquid hydrocarbon or water, and it also is drawn parallel to the shale line. This line is labeled "100" and the distance between this line and the shale line of the neutron curve is called the "total neutron curve deflection." (D_{nt}).

The per cent total curve deflections D_g and D_n, are obtained by dividing the curve deflections opposite a particular depth and zone, measured from the appropriate zero line, by the total deflection in inches of that curve, (the distance between the zero and the maximum lines). This is illustrated in Fig. 8.

The second step in calculating N_p is to determine the values of D_g and D_n by measuring the deflection of the particular zone desired and comparing this value with the total deflection for the gamma ray and neutron curves, respectively. Thus,

$$D_g = \frac{D_{go}}{D_{gt}} \quad \ldots\ldots\ldots\ldots \quad (4)$$

where:

D_{go} is the distance measured from the zero line for the gamma ray curve deflection, and D_{gt} is the distance for total deflection of the curve. Similarly for the neutron curve:

$$D_n = \frac{D_{no}}{D_{nt}} \quad \ldots\ldots\ldots\ldots \quad (5)$$

The logarithms of the values for D_g are then determined from any table of logarithms and the values substituted in Equation (3).

N_p may be calculated more easily, however, by using the nomograph shown in Fig. 9, for here it is only necessary to lay a straight edge across the nomograph, aligning the values of $(D_n + 1)$ and $(D_g + 1)$ on their respective indices and the value for N_p will be found on the N_p index at its point of intersection with the straight edge.

Response of the Neutron Productivity Number

N_p is an index which may indicate the per cent of shale, liquid or gas. The limits described in the following illustration must not be taken as generally applicable, because it was found that these limits apply only in partcular areas. It is necessary that values of N_p be determined and compared with drill stem tests, production tests or perforating data in the particular area or field being considered before the range of values may be known. From such data the following table was compiled:

Values of N_p	Condition
1 to 75	Shale
75 to 168	Liquid Filled Porosity
168 to 500	Gas Filled Porosity

Specific Applications of the Neutron Productivity Number

To illustrate the application of the neutron productivity number in sand areas, wells in the Freites District, Venezuela and the Buffalo Field of East Texas were selected. These wells are thought to have penetrated a relatively uniform porosity throughout the sand bodies.

The first example, shown in Fig. 8, is of a well in the Freites District, Venezuela. The interval 7,295 - 2,323 ft was perforated and on test flowed at the rate of 534 B/D. The maximum value reached by N_p in this interval on the log was approximately 150. The interval 7,445 - 7,455 ft was not tested but is believed by the operator to contain gas. The N_p value of nearly 300 calculated from the log confirms this opinion. The interval 7,480 - 7,660 ft was not tested but is believed by the operator to contain fluid. The value of 120 for N_p tends to confirm this opinion.

The values of N_p were calculated from the log by establishing the reference lines in the manner described previously, and applying D_g and D_n to the nomograph.

Also shown in Fig. 8 is the radioactivity log of the Lone Star Producing Co. Mary Jones No. 4, Buffalo Field. The main Woodbine sand from 5,695 ft to 5,724 ft apparently is a uniformly clean (silt and shale-free) sand. This zone was tested through perforations in the 5½-in. casing from 5,704.5 ft to 5,712.5 ft and produced gas with very little oil. These perforations were squeezed and the casing reperforated from 5,706 ft to 5,714 ft. A completion test of these perforations yielded 81.81 B/D of oil with little gas.

The values for D_g and D_n throughout the entire section were determined, and N_p was calculated from the nomograph (Fig. 9). The gas-oil contact is placed at 5,704 ft with a value of 160 N_p (table above) representing the approximate separation value.

The Lone Star Producing Co. W. D. Recknor No. 1, Buffalo Field, is another example of the application of the table. In this well the 5½-in. casing was perforated from 5,741 ft to 5,745 ft resulting in the production of oil with a low gas/oil ratio. It will be noted that the N_p value at the depth 5,742 ft is 92 and at 5,740 ft the N_p value is 260, placing the gas-oil contact between 5,740 ft and 5,742 ft. Although the section at 5,742 ft is indicated by the gamma ray curve as shaly, the value of 92 after application of the N_p curve would indicate that it should be productive of liquid. The low values of N_p in the interval from 5,728 to 5,736 ft are probably due to the invasion of large quantities of drilling fluid. The sands indicated from 5,754 ft to 5,758 ft are known to be water bearing and were used as the 100 per cent line on the neutron curve. The values of N_p were computed by the use of the nomograph as previously described, Fig. 9. Had the N_p curve not been computed for this log, it would have been difficult to place the gas-oil contact within a two-ft zone due to the influence of shale at exactly the point of contact.

The values established for this field are usable over a limited area and should be improved with each subsequent well that is drilled and tested. The method described here is particularly applicable to the shaly sands in which the influence of shale reduces the intensity of the neutron curve and prevents the visual identification from the neutron curve of gas-liquid interfaces which is possible in clean sands.

SUMMARY AND CONCLUSIONS

The use of a device for determining the position of zero radioactivity and a sensitivity selector switch of greater versatility has been discussed and their application to actual logs of the limestones of West Texas and Kansas has been shown by illustration. Using the new instrumental zero reference line, the application of quantitative methods to the radioactivity logs will provide a means of estimating porosity. This is done by comparing the intensity of the neutron curve deflections with the porosities from the core samples and plotting this relationship to establish a neutron derived porosity curve. This curve may then be applied to unknown wells of similar bore hole conditions on which radioactivity logs have been obtained. The data shown in this paper are applicable to wells having 7-in. cased holes or 6¼-in. open holes in the reef limestone of West Texas and to 4½-in. cased holes in the Lansing-Kansas City zone in Kansas.

A relative method of utilizing an interrelation factor calculated from the gamma ray and neutron curves called the neutron productivity number has been discussed. The neutron productivity number calculated for given depth intervals within the zone of interest will aid the interpretation of radioactivity logs in determining gas-liquid contacts in shaly sands and sandy shales. The use of the neutron productivity number is recognized as a relative method of comparison and is limited in applicability to those areas and reservoirs in which the neutron curve is definitive of gas in the reservoir. Greater

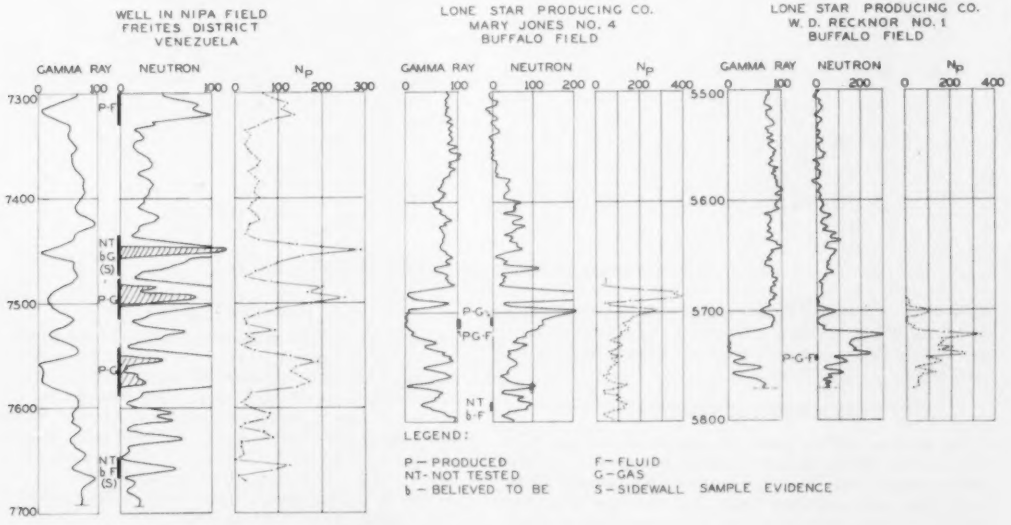

FIG. 8 — APPLICATION OF NEUTRON PRODUCTIVITY NUMBER.

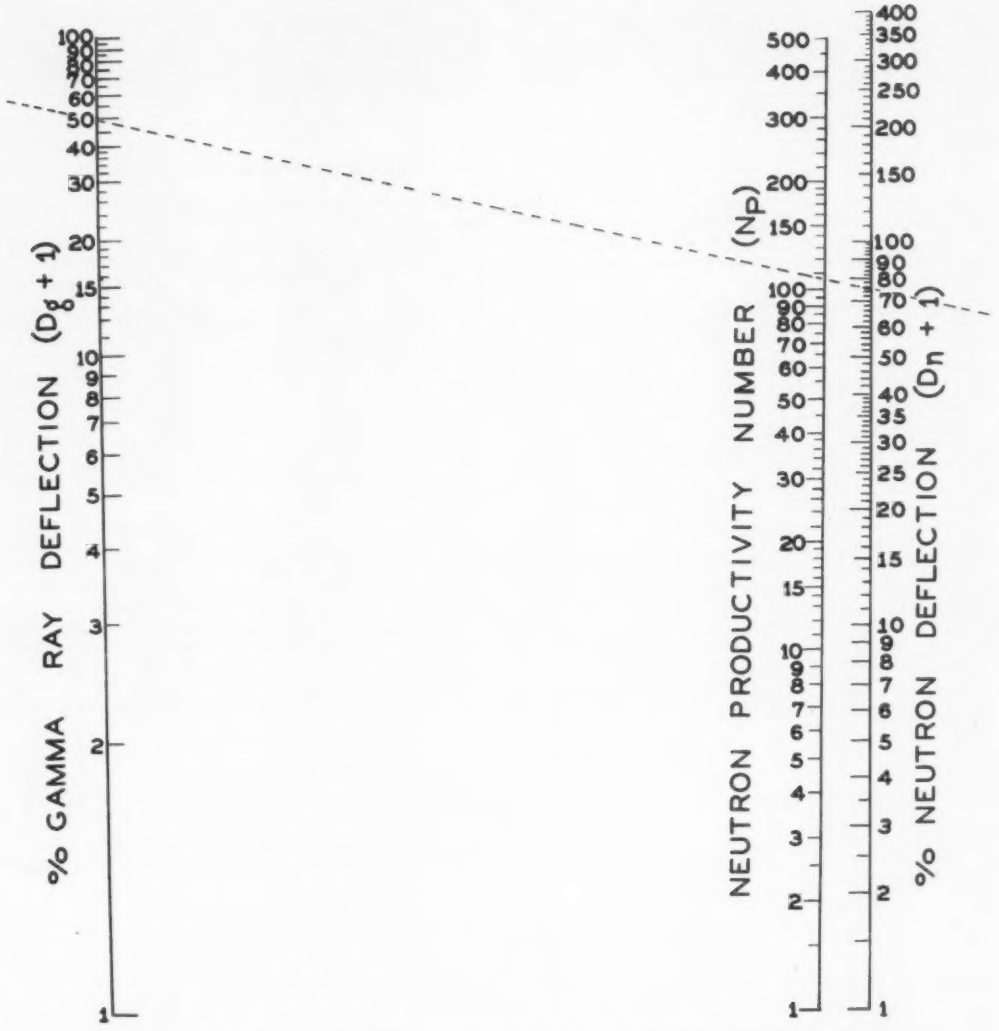

FIG. 9 — NOMOGRAPH FOR COMPUTING THE NEUTRON PRODUCTIVITY NUMBER

versatility and a wider range of applicability may be provided by the use of new radiation zero devices and it is hoped their use will result in an extension of quantitative methods for sand areas.

ACKNOWLEDGMENT

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REFERENCES

1. Green, W. G., and Fearon, R. E.: *Geophysics*, (July, 1940), 5, 272.
2. Pontecorvo, B.: *Oil and Gas Jour.*, (Sept. 11, 1941), 32.
3. Russell, W. L.: AAPG Bul. (Sept., 1941), 25, No. 9.
4. Jackson, W., and Campbell, J. L. P.: *Trans.* AIME, 165, 241.
5. Campbell, J. L. P., and Winter, A. B.: *Oil Weekly*, (Jan. 6, 1946).
6. Mercier, V. J.: *Oil Weekly*, (Oct. 14 and 21, 1946).
7. Fearon, R. E.: *Nucleonics*, (June, 1949), 4, No. 6, 30-92.
8. *Ibid.* (April, 1949), 4, No. 4, 67-75.
9. Bush, R. E., and Mardock, E. S.: *Trans.* AIME, (1950), 189, 19.

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THE SOUTHWEST ANTIOCH GIBSON SAND UNIT

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INTRODUCTION

The Southwest Antioch Oil Field located in T2&3N - R2&3W, Garvin County, Okla., was discovered in February, 1946, by The Globe Oil & Refining Co. and The Vickers Petroleum Co. at their Melinda Gibson No. 1. Oil production was encountered at a depth of 6,525 ft in 14 ft of lower Pennsylvanian sandstone.

The producing sand, locally called the "Gibson" or "Third Deese," is a sand bar deposit strung along the west flank of the Pauls Valley uplift in a northwest-southeast direction. The oil reservoir is defined to the east by the edge of sand deposition along the uplift and to the west by the gradation of sand into shale. Within the Antioch Unit, the sand dips from 150 to 400 ft per mile southwesterly and has a pay thickness varying from 10 to 55 ft and averaging 28 ft.

Several areas of Gibson production have been developed, including the Katie pool on the south, the Elmore Area of the Southwest Antioch Gibson Sand pool, the Southwest Antioch Gibson Sand pool proper, the Southwest Maysville pool and the New Hope pool on the north. Production extends over a belt 22 miles long by about two miles wide and is continuous except into the Katie and New Hope pools. It appears that drilling will soon prove these intervening areas productive. To March 1, 1950, approximately 18,000 acres have been developed with 450 Gibson wells. It is likely this count will ultimately reach 32,000 acres with 800 wells.

RESERVOIR

The natural production of oil from the Gibson reservoir is primarily due to solution gas expansion though gravity also plays a part. There is no indication of water drive or evidence that an initial gas cap existed.

Gibson oil has a stock tank gravity of 43° API and was saturated at the original reservoir pressure of 2,925 psi. It contained 1,340 cu ft of gas per bbl in solution and had a high shrinkage of 70 per cent. Connate water amounts to 15 per cent. Reservoir temperature is 130°F.

Porosity averages 15.5 per cent and permeability ranges from less than one md to over 1,000. Based on measurement of 400 core plugs from 15 wells, 78 per cent of the permeabilities fell within the 10 to 1,000 md bracket and averaged 167.

Primary oil recovery is estimated at 140 bbl per acre-ft or 22 million bbl for the present 137-tract unit. Due to unitization

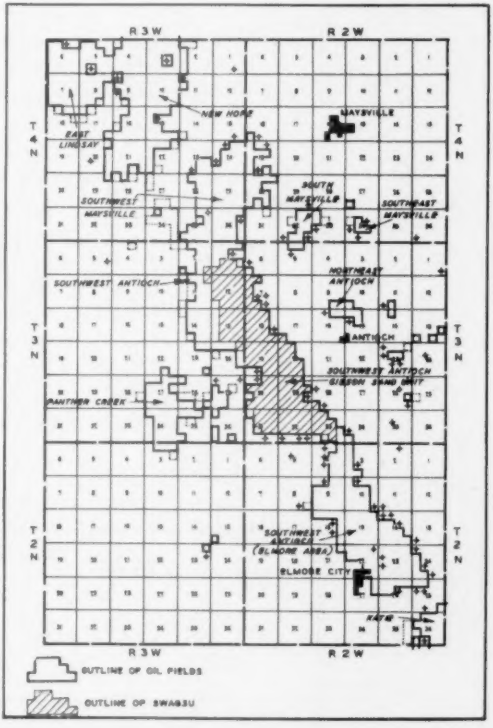

FIG. 1 — MAP SHOWING OIL FIELDS IN VICINITY OF THE SOUTHWEST ANTIOCH GIBSON SAND UNIT.

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and gas injection, it is expected that recovery will be increased to 260 bbl per acre-ft or to a total of 41 million bbl — about doubled.

UNITIZATION

It appeared to oil operators early in the development of the Southwest Antioch pool, that oil recovery could substantially be increased under a program of unit operation and gas injection. This belief was verified by a study completed in February, 1947. It was realized that to put such a program into effect, the full cooperation of royalty owners was necessary and desirable. To this end a meeting of royalty owners was called and operators helped organize the Southwest Antioch Royalty Owners Association.

This association played an important part in creating and perfecting the unit. Their technical experts actively participated in operator's meetings and had access to all information. To keep its membership advised, there were several meetings of the association in the towns of Antioch and Maysville. Operator representatives attended a number of these gatherings to discuss unitization.

On Jan. 6, 1948, the Oklahoma Corporation Commission heard and approved the petition creating the Southwest Antioch Gibson Sand Unit without objection from royalty owners or oil operators. Operation of the 67 wells comprising the original unit was assumed by The Globe Oil & Refining Co. as Unit Operator on April 1, 1948.

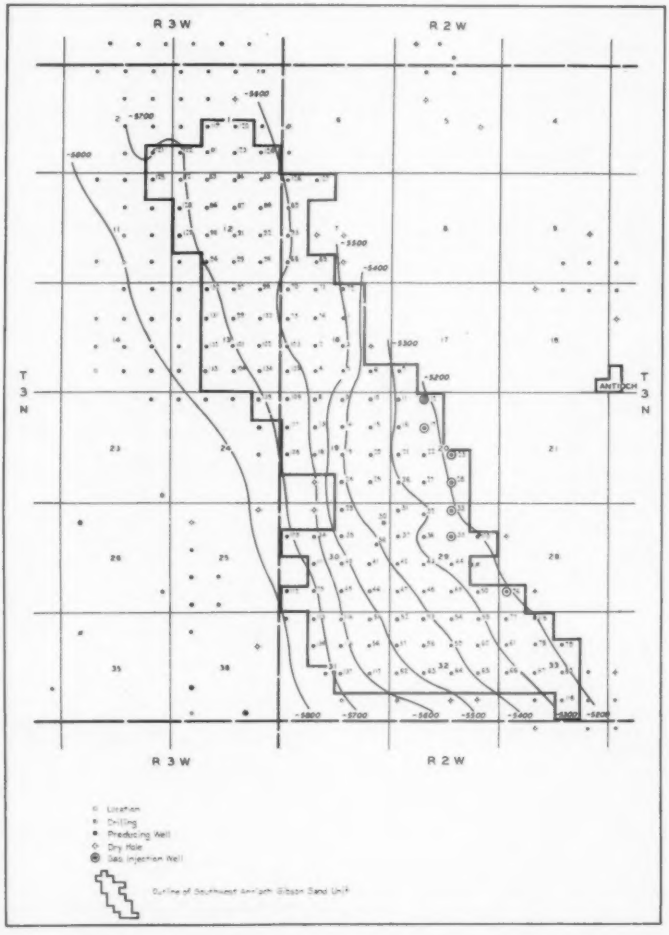

FIG. 2 — STRUCTURE MAP, GIBSON SAND, SWAGSU.

The Antioch Unit has been enlarged three times without incident and has grown in size from 67 to 137 wells. A fourth enlargement is now being considered which will increase this number to approximately 180 wells.

Under the "Plan of Unitization" adopted by the Southwest Antioch Unit, only producing 40-acre tracts are taken in. The original participation formula based half of tract interest on net pay and half on ability to produce up to 150 B/D of oil with a maximum of 375,000 cu ft of gas. The formula has since been modified to include a reservoir pressure factor.

Operation

Operating provisions of the "Plan of Unitization" stipulate: "The oil produced from the Unit Area shall be produced from those wells in the Unit Area from which the same can be obtained with the smallest loss or dissipation of reservoir energy reasonably possible under practical operating conditions as they may exist from time to time;" and

"Gas wells and wells which produce oil with gas/oil ratios found to be excessive in relation to the gas/oil ratios of other wells producing oil from the Unit Area shall be shut in or the production therefrom restricted in such manner as to make the most effective utilization of the gas energy of the reservoir reasonably possible under practical operating conditions as they may exist from time to time."

Production operations from the beginning have been conducted in accordance with these principles. During the first

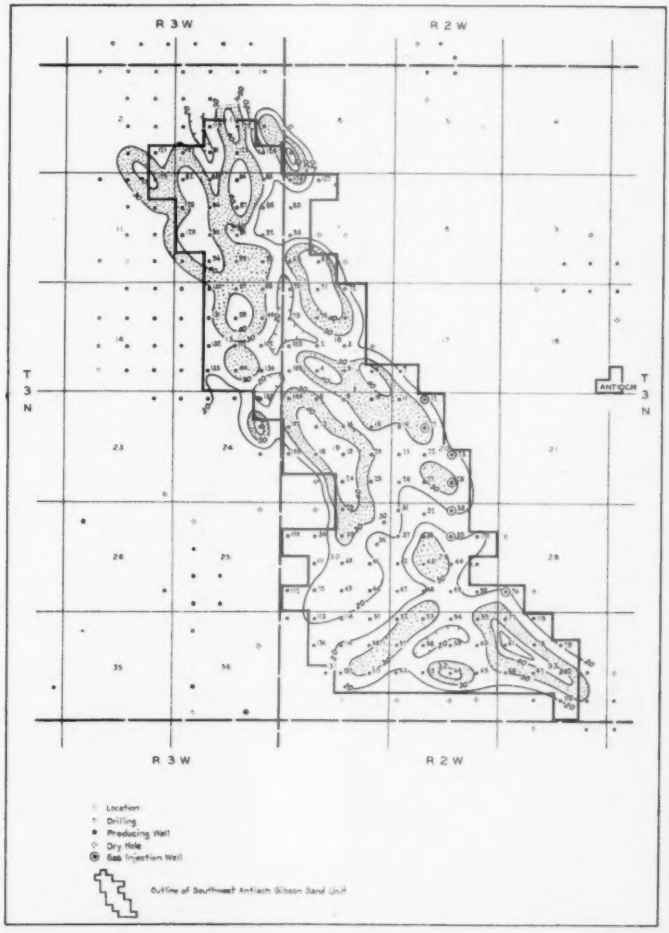

FIG. 3 — THICKNESS MAP, GIBSON SAND, SWAGSU.

month of operation, as a result of selective oil production, average gas/oil ratio for the Unit Area was lowered from 3,000 to 2,200 cu ft per bbl or about a third more oil was produced for the same volume of gas.

In order to determine the amount of oil to be produced from each well and determine the distribution of gas to input wells, gas/oil ratios are taken monthly and reservoir pressures are measured three to four times a year.

Injection

Gas from the Unit is processed and compressed for injection by the plant of the Warren Petroleum Corp., *et al.* Injection of 9 MMcf/D of gas started during August, 1948, with one 600-HP compressor. A second 600-HP machine, which was placed in operation during October, 1948, boosted input to 15.5 MMcf/D. Present capacity of 25 MMcf/D was reached in June, 1949, with the addition of a third 800-HP compressor.

Gas is being returned to the Gibson sand through seven injection wells situated at high structural positions near the sand edge on the east side of the pool. Injectivity rates at individual wells range from 2 MMcf/D to in excess of 5.5 MMcf/D at 2,400 psi pressure. During 21 months operation, a total of over 10 billion cu ft of gas has been put back into the reservoir.

The effects of gas injection were first noticed during the second month of injection when a material lessening in the rate of bottom hole pressure decline occurred near input wells; some wells even showed small pressure increases. At one pro-

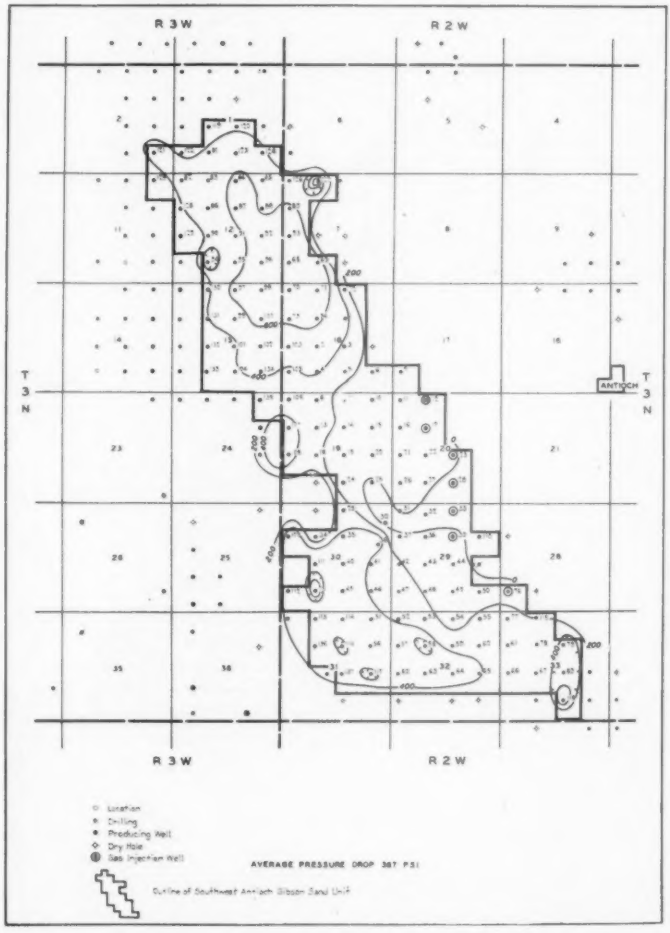

FIG. 4 — BHP CHANGE MAP, SEPTEMBER, 1948, THROUGH FEBRUARY, 1950, SWAGSU.

ducer, during the third month of injection, oil rate tripled and gas/oil ratio fell to one-third. During the fourth month at another well, oil gravity increased from 40° to 60° API. This change in liquid character was caused by injection of gas at a diagonally offsetting well which formerly produced high gravity oil.

The advance of the gas front away from injection wells has been fairly uniform, conforming closely with structure. There has been no tendency for gas to channel or break through. From a comparison of pressure drops at individual wells with the average drop for the Unit since the beginning of injection, it appears gas has influenced 45 wells, an area of about 2,000 acres, and has been felt as far away as 6,500 ft from input wells.

PERFORMANCE

The 137 wells comprising the present Unit have produced a total of 10.8 million bbl of oil to March, 1950. Of this amount 9 million bbl or about 85 per cent has come from the 80 wells in the first enlarged Unit. Inasmuch as a longer history is available on these wells and they have recovered the major portion of the oil, their behavior is a reliable indication of reservoir performance.

At the time of unitization, April 1, 1948, gas/oil ratio was 2,900 cu ft per bbl and was increasing rapidly. Had conventional operation continued, gas/oil ratio by now would be in excess of 10,000. Actually it is 4,800. It appears that a minimum of twice as much oil is now being recovered per cu ft

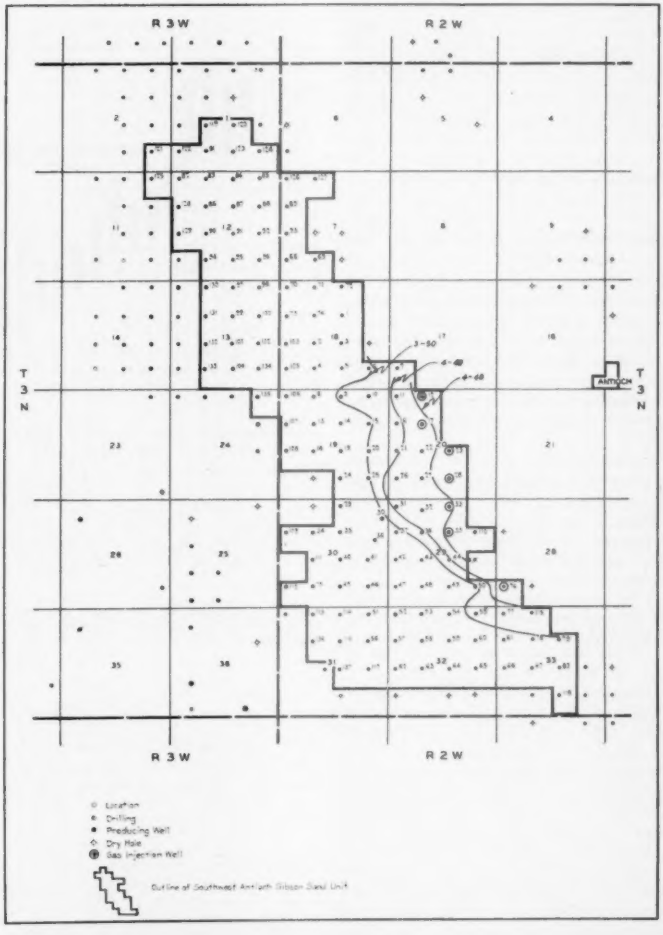

FIG. 5 — TIME-POSITION 10,000 GOR CONTOUR, VICINITY GAS INJECTION, SWAGSU.

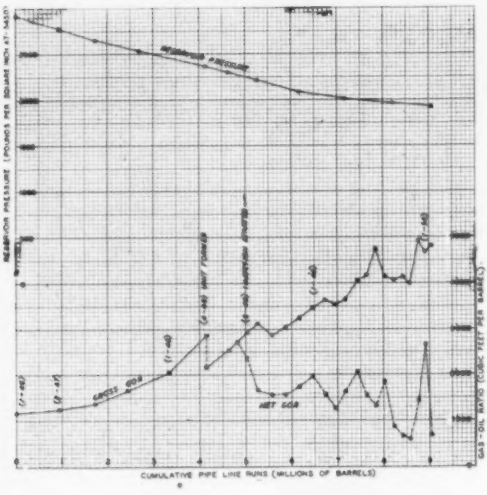
RESERVOIR PRESSURE (POUNDS PER SQUARE INCH AT DATUM)
GAS-OIL RATIO (CUBIC FEET PER BARREL)
CUMULATIVE PIPE LINE RUNS (MILLIONS OF BARRELS)
INTERMITTENT PRESSURE
GAS INJECTION STARTED
CASING GAS
NET GAS

FIG. 6 — RESERVOIR PERFORMANCE, 80 TRACT UNIT, SWAGSU.

of gas than would have been recovered had conventional operation continued.

A total of 5.2 million bbl of oil and 18.1 billion cu ft of gas have been produced under Unit operation and 9.2 billion cu ft of gas have been returned to the reservoir. Net gas/oil ratio has averaged 1,725 cu ft per bbl. This compares to an average ratio of 1,645 cu ft per bbl before unitization, during which period 3.9 million bbl of oil and 6.4 billion cu ft of gas were produced. Considering only the interval of gas injection, 4.2 million bbl of oil have been recovered at a net ratio of 1,565 cu ft per bbl.

The effect of gas injection is readily apparent from an examination of reservoir pressure decline which shows a decided reduction in rate during December, 1948, five months after gas injection started. Prior to this time 7,370 bbl of oil were produced per pound pressure drop. Since this date, each pound drop in pressure has accounted for the recovery of 17,790 bbl or approximately 140 per cent more oil.

The public, much to the harm of unitization, frequently is of the impression that reduced production rate inevitably accompanies unit operation. Comparison with the production rate of competitively operated wells in the Elmore Area of the pool, shows that such a belief is unjustified, at least in the case of the Antioch Unit.

Both groups of wells produce from the same source of supply, wells are very nearly the same age, and the reservoir is approximately in the same state of depletion. The Unit has produced the top allowable rate set by the Corporation Commission; whereas, the average well in the Elmore Area has produced substantially under the maximum allowable. Over a period of 17 months since gas injection started, Unit wells produced an average of 93.5 B/D of oil per well compared to 73.8 B/D for wells in the Elmore area. The difference of 19.7 B/D amounts to the production of 7,200 bbl of additional oil in a year's time from each well in the Unit. To royalty owners this means an increase in annual income of $2,400.00 per well.

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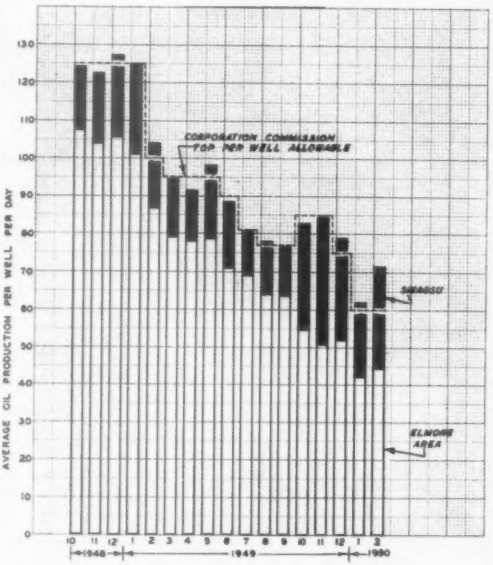

FIG. 7 — COMPARATIVE APPROACH OF SWAGSU AND ELMORE AREA PRODUCTION TO MAXIMUM ALLOWED BY THE CORPORATION COMMISSION.

STEADY FLOW OF TWO-PHASE SINGLE-COMPONENT FLUIDS THROUGH POROUS MEDIA

FRANK G. MILLER,* U. S. BUREAU OF MINES, SAN FRANCISCO, CALIF., MEMBER AIME

ABSTRACT

This report presents developments of fundamental equations for describing the flow and thermodynamic behavior of two-phase single-component fluids moving under steady conditions through porous media. Many of the theoretical considerations upon which these equations are premised have received little or no attention in oil-reservoir fluid-flow research. The significance of the underlying flow theory in oil-producing operations is indicated.

In particular, the theoretical analysis pertains to the steady, adiabatic, macroscopically linear, two-phase flow of a single-component fluid through a horizontal column of porous medium. It is considered that the test fluid enters the upstream end of the column while entirely in the liquid state, moves downstream an appreciable distance, begins to vaporize, and then moves through the remainder of the column as a gas-liquid mixture. The problem posed is to find the total weight rate of flow and the pressure distribution along the column for a given inlet pressure and temperature, a given exit pressure or temperature and given characteristics of the test fluid and porous medium.

In developing the theory, gas-liquid interfacial phenomena are treated, phase equilibrium is assumed and previous theoretical work of other investigators of the problem is modified.

Laboratory experiments performed with specially designed apparatus, in which propane is used as the test fluid, substantiate the theory. The apparatus, materials and experimental procedure are described. Comparative experimental and theoretical results are presented and discussed.

It is believed that the research findings contributed in this paper should not only lead to a better understanding of oil-reservoir behavior, but also should be suggestive in regard to future research in this field of study.

INTRODUCTION

In recent years much time and effort has been consumed in both theoretical and experimental studies of the static and dynamic behavior of oil-reservoir fluids in porous rocks. Although lack of sufficient basic oil-field data, principally concerning the properties and characteristics of reservoir rocks and fluids, largely precludes quantitative application of research results to oil-field problems, qualitative application has become common practice. In effect, oil-reservoir engineering research is serving as a firm foundation for oil-field development and production practices leading to increased economic recoveries of petroleum. This province of research, however, still poses many perplexing problems.

The thermodynamic behavior of two-phase fluids moving through porous media constitutes one facet of reservoir-fluid-flow research that has not received the attention it deserves. This report embodies a theoretical discussion of this subject and a description of a series of related laboratory experiments. The significance of the problem to oil field operations is indicated but in particular the report centers around a theory and method for analyzing the steady, macroscopically linear, two-phase flow of a fluid (a single molecular species) through a horizontal column of porous medium.

For simplicity in showing how the thermodynamic behavior of two-phase fluids moving through porous media affects oil-reservoir performance problems, attention is focused temporarily on a particular well producing petroleum from an idealized water-free solution-gas drive reservoir, the reservoir rock being a horizontal, thin, fairly homogeneous sandstone of large areal extent confined between two impermeable strata.

The flowing hydrocarbon fluid is considered to exist entirely as a liquid at points in the reservoir remote from the well; however, the decline in fluid pressure in the direction of the well causes vaporization of the hydrocarbon to begin at a radial distance r from the well. Upstream from r the fluid moves entirely as a liquid and downstream from r it moves either entirely as a gas or as a gas-liquid mixture depending on the properties of the hydrocarbon and on the thermodynamic process it follows during flow.

The distance r would be variable under transient flow conditions, but for purposes of analysis the flow is considered to be steady at the particular instant of observation during the flowing life of the well of interest. If the flow were isothermal and the hydrocarbon a pure substance, the fluid would be entirely gaseous downstream from r. Thus, this isothermal flow process for a pure substance would require that the heat of vaporization be supplied at r, over zero length of porous medium, at the precise rate necessary to maintain the constant temperature. This means that the solid matrix of the porous medium (reservoir rock) and the surroundings (impermeable strata confining the reservoir rock) would have to serve as infinite heat sources. Heat-transfer requirements would be somewhat less severe for the isothermal flow of a multicomponent hydrocarbon as bubble and dew points at the same temperature correspond to different pressures. In this instance isothermal conditions would be sustained without complete vaporization of the fluid over zero length of porous medium.

Nevertheless, as the flow is in the direction of decreasing

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*This paper is a report of part of the research performed by the author in fulfilling the requirements for a PhD degree in mechanical engineering at the University of California.

pressure, isothermal flow of either a single-component or multi-component hydrocarbon represents a maximum limiting condition as no other thermodynamic, decreasing-pressure, vaporization process would require as great a rate of heat transfer to the fluid. In contrast, a minimum limiting condition is represented by a thermally-isolated flow system, defined as one in which no heat is transferred to the flowing fluid from the solid matrix of the porous medium or from the impermeable strata confining the system.

As pointed out by O'Brien and Putnam[1] the flow conditions in an oil reservoir apparently are intermediate between the foregoing maximum and minimum limiting conditions. Those authors indicate that a petroleum-bearing stratum could be represented by a fluid-filled porous medium, confined above and below by constant-temperature impermeable beds from which heat is transferred along various paths, solid and fluid, through the porous media. Flow problems relating to this system, however, depend on complete knowledge of the heat-transfer characteristics of the system and such information is not presently available. In this connection O'Brien and Putnam indicate further that isothermal and adiabatic flow may be very nearly the same for the flow of a crude oil and natural gas mixture in an oil reservoir. They cite an example pertaining to the adiabatic flow of such a mixture and show that the fluid temperature drops only a few degrees for a drop in pressure from 3,000 to 400 psia.

The laboratory study described in this report is based on the foregoing considerations. In an effort to start with the simplest appropriate two-phase flow system it was deemed advisable to investigate the two-phase flow behavior of a single-component fluid. This restriction rules out isothermal flow as a single component will not flow isothermally in two phases. Accordingly, adiabatic conditions were adopted.

In studying the adiabatic system it was found necessary to modify and extend the O'Brien-Putnam flow theory. The modified theory, concerning fundamental relations between rates of flow and pressure differentials, is substantiated by the experiments.

SCOPE OF PROBLEM

The investigation described in this paper is intended to contribute to the solution of the general problem of determining the flow behavior of oil-reservoir fluids in subsurface porous rocks. It is well known that this general problem represents a large field of widely diversified research in the petroleum producing industry. The scope of the present work is confined to the development and test of equations that describe the flow and thermodynamic characteristics of a single-component two-phase fluid moving through a porous medium under conditions of adiabatic flow.

The fluid-transmitting capacity and the geometry of the porous medium have no direct bearing on the principles of the analysis. For convenience, therefore, the test flow system was made by packing a suitable conduit with a clean, previously sized unconsolidated sand. As the bulk cross-sectional area of the resultant sand column was sensibly constant, the flow was macroscopically linear. Propane was selected as the test fluid. Adequate thermodynamic and viscosity data[2,3] are available for this substance. Moreover, a hydrocarbon fluid was selected in preference to other fluids because of the interest of the oil-producing industry in the behavior of hydrocarbons. To simplify the analysis the flow was specified as steady.

In conformance with the preceding discussion the flow system was designed to prevent transfer of heat between the flowing fluid and its surroundings (the sand grains and the walls of the flow conduit). Furthermore, in the experiments, the propane entered the column of sand as a liquid, began to vaporize an appreciable distance from the inlet and discharged from the column as a gas-liquid mixture.

To avoid the introduction of unnecessary complications regarding the meaning of pressures measured in the two-phase flow portion of the system, the column of sand was installed in a horizontal position.

Five flow experiments were performed. Total (gas plus liquid) weight rates of flow were measured and pressure and temperature distribution data were collected.

The ensuing theory, substantiated by the propane-flow experiments conducted with the described flow system, discloses that gas and liquid weight rates of flow as a function of distance along the sand column, and pressure and temperature distributions, may be calculated if the inlet pressure and temperature and the outlet pressure or temperature are given. In addition, pressure and temperature distributions and gas and liquid weight-rate-of-flow distributions, may be calculated if the constant total weight rate of flow and the inlet pressure and temperature, are given.

In developing the theory, capillary phenomena are treated. Based on the work of Aboul-Seoud,[4] it is assumed that phase equilibrium is attained at all cross-sections of the column of sand perpendicular to the direction of flow.

THEORY

Nomenclature

The symbols used in mathematical analyses in this report are as follows:

x = distance along column of porous medium
x_a = value of x at which vaporization begins
L = subscript denoting liquid
G = subscript denoting gas
W = weight rate of flow (with no subscript, W = total weight rate $= W_G + W_L$)
H = enthalpy per unit weight of fluid
U = kinetic energy per unit weight of fluid
P = fluid pressure
P_1 = fluid pressure at upstream end of column of porous medium
P_2 = fluid pressure at downstream end of column of porous medium
P_a' = equilibrium, plane-surface, vapor pressure
T = absolute temperature
f = weight of gas per unit weight of gas-liquid mixture passing a transverse section of column in unit time
$\bar{f}$ = weight of gas per unit weight of gas-liquid mixture instantaneously at a transverse section of column
Q = volumetric rate of flow (with no subscript, Q = total volumetric rate $= Q_G + Q_L$)
$\hat{v}$ = specific volume
A = bulk cross-sectional area of column of porous medium
ε = fractional porosity
ρ = wetting-phase content (fraction of pore space occupied by liquid)
t = time variable
u = average miscroscopic velocity
k = homogeneous-fluid permeability
k_L = permeability to liquid (with gas present)
k_G = permeability to gas (with liquid present)
μ = absolute viscosity
$F_L(\rho) = k_L/k$
$F_G(\rho) = k_G/k$

[1]References given at end of paper.

$F(P)$ = pressure function = $\left[\frac{k_L/k}{\mu_L \bar{v}_L} + \frac{k_G/k}{\mu_G \bar{v}_G}\right]$

P_c = capillary pressure
R = universal gas constant
M = molecular weight of gas

Development of Flow Equations

For steady two-phase (gas-liquid mixture) flow, continuity principles immediately lead to

$$\frac{dW_G}{dx} + \frac{dW_L}{dx} = 0 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

or

$$W_G + W_L = W = \text{constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The general energy equation, which is premised on conditions of steady flow, provides means for determining the thermodynamic process undergone by the flowing fluid. Regarding that equation, it is evident that the described flow system involves no "shaft work" and that the horizontal position of the column implies no changes in potential energy. Therefore,

$$dH + dU = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Equation (3) is not limited to single-phase flow; it applies equally well to two-phase flow. In either instance, however, H and U are to be based on a unit weight of fluid flowing.

If it is assumed that Darcy's law is valid for the system under discussion, viscous forces would predominate and the heat energy generated by friction would be very large compared to kinetic energy changes. Thus, for any two transverse sections in the system, a finite distance apart,

$$\triangle H = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

hence,

$$H = \text{constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

which means that the fluid follows an isenthalpic process. As a consequence the fluid will flow in two phases (gas and liquid) if the (H, T) or (H, P) conditions along the column fall within the two-phase region on an ordinary thermodynamic chart for the test fluid (Fig. 1).

Based on Equations (2) and (5) the enthalpy of the fluid passing any transverse section in the column in unit time is given by

$$W_L H_L + W_G H_G = WH = \text{constant} \quad . \quad . \quad . \quad . \quad (6)$$

Suppose that the fluid enters the column (at $x = 0$) entirely as a liquid but that the flowing-fluid pressure has become reduced to its saturation intensity at x_0. For an isenthalpic process the fluid must exist downstream from x_0 as a gas-liquid mixture. Under these conditions the flowing fluid would follow a path as represented by path ABC in Fig. 1.

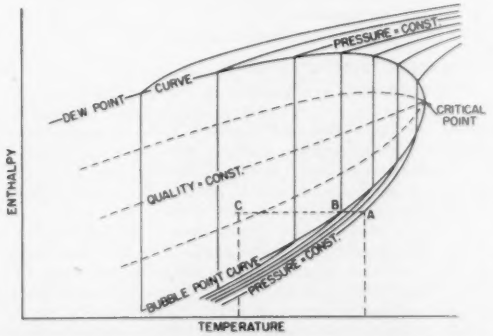

FIG. 1 — SCHEMATIC ENTHALPY-TEMPERATURE CHART FOR PROPANE (AFTER O'BRIEN AND PUTNAM).

In unit time a weight W of liquid enters the column, and during the same unit of time a weight W_L of liquid and W_G of gas departs from any arbitrarily selected transverse section at x. Thus, for the length of column bounded by zero and x, the fraction (f) that vaporizes, of an original unit weight of entering liquid, may be expressed by

$$f = \frac{W_G}{W} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Substituting in Equation (2),

$$1 - f = \frac{W_L}{W} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

hence,

$$\frac{1-f}{f} = \frac{W_L}{W_G} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Equation (6) becomes

$$(1-f)H_L + fH_G = H \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

or

$$f = \frac{H - H_L}{H_G - H_L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

In the thermodynamics of single-component static systems, the righthand member of Equation (11) is a well-known expression for "quality," the weight of gas present in a unit weight of a gas-liquid mixture. For a static system H would be the enthalpy per unit weight of mixture present, and H_G and H_L the respective enthalpies per unit weight of gas and liquid present. For the foregoing dynamic system (see Equation 6), it has been shown that an isenthalpic process is one which requires the enthalpy of the fluid passing any transverse section in unit time to be the same for all transverse sections of the column. Consequently, for a dynamic system enthalpies are to be expressed on a per-unit-weight-of-fluid-flowing basis. As charts like Fig. 1 are prepared from data collected with static systems, it is desirable to show how they may be applied to dynamic systems of the kind under discussion.

In this respect, suppose that it is possible to separate and collect the gas and liquid discharged in unit time from the transverse section at x. If the collected gas is kept entirely in the gaseous state at the pressure and temperature at x, it will be saturated and occupy a volume Q_G, numerically equal to the volumetric rate of gas flow at x. Likewise, if the collected liquid is kept entirely in the liquid state at the pressure and temperature at x, it will be saturated and occupy a volume Q_L, numerically equal to the volumetric rate of liquid flow at x. Furthermore, if these collected and separated fluids are recombined to the total volume $(Q_G + Q_L)$ without change in their common pressure or temperature, the weights of gas and liquid in the resultant mixture will be equivalent numerically, to the respective weight rates of flow of the two phases at x, namely W_G and W_L. The quality of the resultant mixture, therefore, will be W_G/W.

Accordingly, the quality of the mixture *passing* x in unit time is W_G/W, which is f (Equation 7). Hence, the lines of constant quality on Fig. 1 are lines along which the fraction vaporized (f) is constant.

Again considering the foregoing hypothetically collected and recombined fluid, produced from transverse section x in unit time, the specific volumes of the collected gas and liquid, respectively $\bar{v}_G$ and $\bar{v}_L$, are equal to Q_G/W_G and Q_L/W_L; thus, the specific volume of the resultant mixture as a whole is given by

$$\bar{v} = \frac{Q_L + Q_G}{W_L + W_G} = \frac{Q}{W} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

It follows that $\bar{v}$ is the specific volume of the mixture passing x in unit time.

It is to be emphasized that the weight fraction of gas in

the *mixture instantaneously at x* is quite different than the weight fraction of gas in the *mixture passing x in unit time.*

In this respect the weight of gas instantaneously in an elemental length δx of the column, upstream but adjacent to x, is $(1/\bar{v}_G)\ [A \cdot \delta x \cdot \varepsilon \cdot (1-\rho)]$ and the weight of liquid is $(1/\bar{v}_L)\ (A \cdot \delta x \cdot \varepsilon \cdot \rho)$ so that the weight fraction $\bar{f}$, of gas in the element is

$$\bar{f} = \frac{1}{1 + \left(\frac{\rho}{1-\rho}\right)\frac{\bar{v}_G}{\bar{v}_L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

To find a corresponding expression for the weight fraction of gas in the mixture passing x in unit time, attention is focused on average microscopic velocities of the two phases. In this connection, the liquid is assumed to be the wetting phase and the gas the nonwetting phase. Part of the gas may be stationary in the form of discrete bubbles enlodged in pores surrounded by liquid. Part of the liquid may be stationary owing to the blocking of its passage through gas-locked pore channels. Neglecting pressure differentials, at x, across curved gas-liquid interfaces, the enthalpies of the flowing gas and stationary gas are the same because they are subjected to the same pressure and temperature. Similar reasoning applies to the liquid.

Let the average particle of liquid at the upstream end of the foregoing elemental length of column reach station x in time δt, and the average particle of gas reach station x in time $\delta t'$. Then, as δx may be made arbitrarily small, the average microscopic velocity of the liquid in the macroscopic direction of flow, at x, is $(\delta x/\delta t) = u_L$; likewise, the corresponding microscopic velocity of the gas is $(\delta x/\delta t') = u_G$.

Based on continuity principles

$$W_G = \frac{A \cdot \varepsilon \cdot (1-\rho) u_G}{\bar{v}_G} \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

$$W_L = \frac{A \cdot \varepsilon \cdot \rho u_L}{\bar{v}_L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

hence,

$$f = \frac{W_G}{W_G + W_L} = \frac{1}{1 + \frac{\bar{v}_G}{\bar{v}_L}\left(\frac{\rho}{1-\rho}\right)\frac{u_L}{u_G}} \quad . \quad . \quad . \quad (16)$$

Comparison of Equations (13) and (16) indicates that $\bar{f}$ and f are equal only if u_L and u_G are equal. The relationship between these microscopic velocities can be investigated by application of Darcy's law to the two phases independently* and by recourse to Equations (14) and (15):

$$W_L = \frac{A \cdot \varepsilon \cdot \rho \cdot u_L}{\bar{v}_L} = -\frac{Ak_L}{\mu_L \bar{v}_L} \cdot \frac{dP}{dx} \quad . \quad . \quad . \quad . \quad (17)$$

$$W_G = \frac{A \cdot \varepsilon \cdot (1-\rho) u_G}{\bar{v}_G} = -\frac{Ak_G}{\mu_G \bar{v}_G} \cdot \frac{dP}{dx} \quad . \quad . \quad (18)$$

from which

$$\frac{u_L}{u_G} = \frac{k_L}{k_G}\frac{\mu_G}{\mu_L}\left(\frac{1-\rho}{\rho}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

$$= \frac{F_L(\rho)}{\rho} \cdot \frac{(1-\rho)}{F_G(\rho)} \cdot \frac{\mu_G}{\mu_L} \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

Knowledge of fluid viscosities and of the characteristics of relative permeability curves (for example, see References 5, 6 and 7), shows conclusively that it would be wholly fortuitous for the righthand member of Equation (20) to equal unity; hence, u_L and u_G cannot be assumed equal. Consequently, it would be invalid to assume equality of f and $\bar{f}$ as was done by O'Brien and Putnam (X in their nomenclature is the same as $\bar{f}$ in this report).

Applying Darcy's law, Equation (2) becomes

$$W = -Ak\left[\frac{k_L/k}{\mu_L \bar{v}_L} + \frac{k_G/k}{\mu_G \bar{v}_G}\right] \cdot \frac{dP}{dx} \quad . \quad . \quad . \quad (21)$$

Integrating over a length of column between the inlet end of the column and an arbitrarily selected transverse section at x:

$$Wx = Ak \int_{P}^{P_i} F(P)dP \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

in which $F(P)$, the pressure function, is equivalent to the term in brackets in Equation (21), and P_i the fluid pressure at the inlet.

Equation (22) may be used to determine the theoretical discharge rate, W, from the system. In this instance let x be the total length of the flow column, causing P to be the outlet pressure. If small increments of pressure are taken along path ABC in Fig. 1, then Equation (11) may be used to determine the distribution of f along the column. O'Brien and Putnam advanced this method of calculation, but in using f as though it were the same as $\bar{f}$ they applied Equation (13) — setting f equal to the righthand member of that equation — thereby calculating ρ erroneously. They then used the incorrect values of ρ in conjunction with relative-permeability curves to obtain k_L/k and k_G/k. Thus, their theory requires modification.

In this respect, it is only necessary to use Equation (9) for determinations of distributions of k_L/k and k_G/k. From Equations (17) and (18):

$$\frac{W_L}{W_G} = \frac{k_L}{k_G} \cdot \frac{\mu_G}{\mu_L} \cdot \frac{\bar{v}_G}{\bar{v}_L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

Substituting for (W_L/W_G) in Equation (9) and rearranging terms,

$$\frac{k_L}{k_G} = \frac{\mu_L \bar{v}_L}{\mu_G \bar{v}_G}\left(\frac{1-f}{f}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Equation (24) can be used to determine the k_L/k_G — ratio of relative permeabilities — distribution along the column. Relative-permeability data show k_L/k, k_G/k and k_G/k_L as functions of ρ; hence, with the k_L/k_G distribution known, it is possible to plot $F(P)$ against P. The area under the resulting curve, between the limits of P_i and P represents the value of the integral in Equation (22). It follows that W may be calculated.

With the theoretical total weight rate of discharge established, Equation (22) may be applied further to determine the theoretical pressure distribution. To accomplish this calculation, successive values of P (less than the inlet pressure and greater than the outlet pressure) are selected. In each instance the integral of Equation (22) is evaluated graphically and corresponding values of x determined.

Gas-Liquid Interfacial Curvature

Charts like Fig. 1 are based not only on equilibrium thermodynamics, but are constructed from data collected with instruments that cause gas-liquid interfaces to be, sensibly, plane surfaces. In the foregoing analysis, therefore, it is assumed that equilibrium thermo-dynamics applies and that the curved surfaces of gas-liquid phase separation in the porous medium may be treated, thermodynamically, as plane surfaces.

According to the kinetic theory there is a continuous exchange of molecules between the phases of a single-component gas-liquid mixture, phase equilibria being attained when the rate of vaporization and rate of condensation are equal. Aboul-Seoud[4] has made a theoretical proof, substantiated by experiment, indicating that phase equilibrium is attained almost instantaneously in a single-component two-phase flow system of the kind under discussion.

*Wyckoff and Botset[5] were the first investigators to apply Darcy's law in two-phase flow.

It is desirable, however, to indicate the effects of gas-liquid interfacial curvature and disclose a means for determining whether capillary pressures are negligible. By definition

$$P_c = P_G - P_L \quad \ldots\ldots\ldots\ldots \quad (25)$$

hence, the gradient of the capillary pressure in a direction x is given by

$$\frac{dP_c}{dx} = \frac{dP_G}{dx} - \frac{dP_L}{dx} \quad \ldots\ldots\ldots\ldots \quad (26)$$

It is pointed out that Equations (25) and (26) have been derived for static systems only. As a first approximation, therefore, suppose that Equation (26) applies to the gas-liquid mixture instantaneously at an arbitrarily selected transverse section in the two-phase flow portion of the test column of porous medium. Then, the pressure gradients in Equations (17) and (18) would differ by (dP_c/dx).

Considering that the liquid and gas respectively are the wetting and nonwetting phases, the Kelvin-Helmholtz equation,[9,9] pertaining to static equilibrium at curved surfaces of gas-liquid phase separation, may be written

$$P_c = P_G - P_G' + \frac{RT}{M\bar{v}_L} \ln \frac{P_G'}{P_G} \quad \ldots\ldots \quad (27)$$

Assuming that this equation applies at any arbitrarily selected transverse section in the two-phase flow portion of the column of porous medium, and substituting for P_c from Equation (25), results in

$$P_L = P_G' - \frac{RT}{M\bar{v}_L} \ln \frac{P_G'}{P_G} \quad \ldots\ldots\ldots \quad (28)$$

As the liquid is the wetting phase $P_G' > P_G$; hence, $P_L < P_G'$. Therefore, if liquid pressures and temperatures are measured along the column of porous medium in the direction of flow and in the two-phase flow portion of the system, gas-liquid interfacial curvature would be manifest by liquid temperatures greater than the normal (plane-surface) saturation temperatures corresponding to the measured pressures.

The same line of reasoning indicates that gas-liquid interfacial curvature is unimportant, thermodynamically, if the corresponding values of the liquid pressures and temperatures are plotted on a pressure-temperature diagram and found to coincide, within the limits of experimental accuracy, with the normal (plane-surface) equilibrium vapor-pressure curve. Under these conditions, $P_L = P_G'$, and from Equation (28) it follows that $P_G' = P_G$; thus $P_c = 0$ and $(dP_c/dx) = 0$.

Equation (22) was developed without consideration of a capillary-pressure gradient distribution (Equation 26) along the two-phase fluid portion of the flow column. Experimental verification of the flow theory — applying Equation (22) — will depend, therefore, on whether capillary pressure gradients are negiligible.

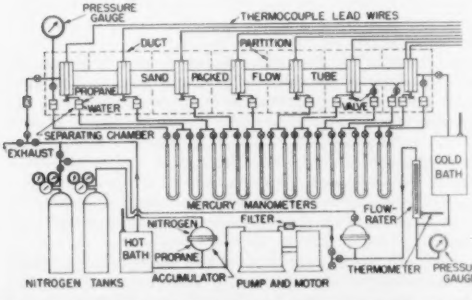

FIG. 2 — SCHEMATIC DIAGRAM OF APPARATUS USED IN PROPANE-FLOW EXPERIMENTS.

In conformance with Muskat's[9] reasoning pertaining to the characteristics of "capillary pressure-desaturation" curves, the existence of the "equilibrium gas saturation" will preclude any discontinuity in capillary pressure at the transverse section in the flow column where vaporization begins. Recognizing, moreover, that vaporization is a continuous process throughout the two-phase fluid portion of the system, there would be no discontinuous accumulation of the wetting phase at the outlet end of the column. Consequently, if, also, there are no stratification discontinuities in the porous medium comprising the column, there will be no discontinuities in the distribution of capillary pressure along the column. Thus, negligible capillary pressure may be taken as tantamount to negligible capillary-pressure gradients.

For a single-component liquid in the vicinity of the saturated liquid line (path AB, Fig. 1), $(\partial T/\partial P)_H$ usually is quite small. For this reason the isenthalpic process followed by the flowing liquid in the all-liquid flow portion of the system will very nearly coincide with an isothermal process. If, therefore, a normal vapor-pressure chart is plotted and pressure and temperature distribution data, collected from the experimental flow system, are superimposed upon the chart, the all-liquid flow portion of the system should be indicated by a series of points forming a straight line parallel to the pressure axis, the pressures corresponding to these points being greater than the saturation pressure corresponding to their common temperature. Points based on data collected in the two-phase fluid portion of the system will fall, within the limits of experimental accuracy, on the vapor-pressure curve, if capillary pressures are negligible. This procedure for plotting data was followed with respect to the ensuing propane-flow experiments. The results indicate isothermal flow in the all-liquid flow portion of the column of sand and that capillary pressures are small.

It is of further significance to note that the foregoing straight line through pressure-temperature points representing all-liquid flow, may be extrapolated to the vapor-pressure curve to find the pressure and temperature at which vaporization begins. These data together with the experimentally-determined pressure and temperature distribution curves will serve to indicate the transverse section at which vaporization begins.

EXPERIMENTAL EQUIPMENT AND TECHNIQUE

Apparatus

The apparatus used in making the experimental study of the adiabatic, two-phase, steady flow of propane through a horizontal column of sand is illustrated schematically in Fig. 2. The flow tube was about five ft long and was constructed from six lengths of nominal two-in. diameter "extra-streng" steel pipe, connected together in a line by forged-steel flanges.

The flange-type units at the extreme ends of the sand-packed conduit were made by drilling, tapping and otherwise preparing blind flanges to provide the confined column of sand with an entry and exit for the test fluid. Blind flanges also were used to construct the flange-type units to which manometer lines and thermocouple lead wires are connected (Fig. 2). Each of these special units was equipped with a built-in ring-type piezometer, similar to the kind made by Wyckoff and Botset,[5] and was machined to accommodate a fluid-tight, electrically insulated coupling device, which permitted insertion of the thermocouple junctions (copper-constantan) in the system and in the sand, without the necessity for conventional thermocouple wells.

The flow tube composed of the pipe sections and flange units was covered with a layer of heat-insulating material (mag-

nesite) about one-half in. thick (this coating is not shown in the sketch). Furthermore, the tube as a whole was enveloped, as shown, by a circular, compartmented sheet-metal air duct. Hot and cold air lines leading to each compartment provided the means for fixing the temperature distribution in the air along the outside of the flow tube to correspond to the temperature distribution of the flowing propane inside the tube. In this respect, the thermocouple circuit (not detailed in the sketch) that was used, was arranged so that temperature differences between the outside and inside of the flow tube could be detected.

The separating chambers were made from nominal 1½-in. diameter steel pipe and were about two in. long. They were an integral part of the manometer lead lines and were mounted on the sand-packed flow tube, inside the sheet-metal duct. During a two-phase flow experiment and while pressures were being measured, the propane in each chamber along the two-phase flow portion of the column of sand existed as a saturated liquid in connection with and at the temperature of the fluid inside the main conduit. Liquid water separated the propane in the chambers from the mercury in the manometers.

The pressure gauge at the inlet end of the system was an accurately-calibrated test gauge having a maximum capacity of 300 psi and a least count of one psi.

Each of the manometers was a glass *U*-tube assembly long enough to indicate a maximum deflection of 48 in. in the mercury levels in the two limbs and strong enough to withstand a total fluid pressure of at least 265 psia. All the manometer lead lines were copper tubing, equipped with brass needle valves and Imperial fittings.

The first manometer on the left (Fig. 2) indicated the pressure drop across the inlet to the flow system. The entering liquid first passed through a Tyler 200-mesh copper retaining screen, against which the sand was packed, and then diverged to fill the sand column. Similarly, the last manometer on the right indicated the pressure drop across the outlet, which also was provided with a retaining screen, and which caused convergence of the flow lines. The intermediate manometers, as shown, indicated pressure differences across various longitudinal sections of the column of sand.

The gas-liquid mixture discharging from the flow tube was conducted through a refrigeration unit to condense it. This unit was a thermostatically controlled water bath through which the discharge line passed in the form of a coil of copper tubing. The propane that departed from the cold bath was entirely liquid and remained in this state until it returned to the column of sand. The total weight rate of flow was determined by metering the condensed propane with a rotameter (commercially known as a Flowrater). This instrument was calibrated with liquid propane as the test fluid, over a range of pressures and temperatures. Accordingly, the pressure and temperature at the meter, as well as the meter reading, were recorded during each flow experiment.

The propane that departed from the Flowrater was passed through a porous-meter filter and then through a two-cylinder, variable-speed, diaphragm-type, reciprocating pump, to increase its pressure. The pistons of the pump displaced lubricating oil, which, in turn, caused a reciprocating motion of a flexible, corrosion-resistant, metal diaphragm, separating the propane from the lubricating oil.

The propane discharged by the pump was conducted through the hot bath (thermostatically controlled) to raise its temperature and was then conducted through another porous-metal filter before re-entering the column of sand.

Each of the two accumulators shown (Fig. 2) was made from two hollow hemispheres of steel, bolted together with a flange joint. The two halves of each accumulator were separated at the flange joint by a flexible, fluid-tight diaphragm, the upper half of the unit having been filled with nitrogen gas in connection with a tank of nitrogen and the lower half having been filled with propane in connection with the propane-flow line. The pressure regulator and two pressure gauges at each tank of nitrogen were used to measure the pressure in the nitrogen tank and to control and measure the pressure of the nitrogen in the accumulator. The accumulator at the right (Fig. 2) was used primarily to dampen pulsations in the propane-flow line and thereby facilitate reading of the Flowrater, and the accumulator on the left was used to increase and decrease the quantity of propane in the propane-flow circuit.

Materials

The propane used in the two-phase flow experiments contained 99+ mol per cent propane. The purity was tested by collecting vapor-pressure data at a few temperatures within the range of interest. The results were compared to the published data of Sage, Schaafsma, and Lacey[3] and the agreement was good.

A steam-cleaned Monterey beach sand was selected as the raw material for preparation of the synthetic sand used in the propane-flow experiments. Visual inspection of this beach sand disclosed that it was composed predominantly of quartz grains, with a moderate proportion of feldspars and a very small percentage of ferromagnesian minerals. It contained a trace of calcareous material (apparently fragments of sea shells), but no organic matter was evident.

This raw stock was used as the source from which a supply of each of seven size fractions of sand grains was obtained. The four coarsest size fractions desired, nominally 14-28, 28-35, 35-48, and 48-65 Tyler mesh, were separated from the Monterey beach sand directly and in sufficient quantity with the appropriate nest of sieves and a sieve shaker. It was necessary, however, to grind the raw material in a ball mill before the three finer fractions, nominally 65-100, 100-200 and 200-325 Tyler mesh, could be recovered in sufficient quantity with the sieves and shaker.

The four coarsest fractions were "de-dusted" by washing them thoroughly with tap water. Following this operation, they were treated with concentrated hydrochloric acid to remove acid-soluble material and washed on a filter with tap water until the filtrate would fail to change the color of blue litmus paper. Finally, they were dried by placing them in an oven at 350°C for 72 hours.

The fineness of much of the material from the mill caused agglomerates to form on the screens during the sieving operations with the three finest fractions. These operations, therefore, were followed with a more refined secondary process of size fractionation. In this respect, each of the three products obtained from the sieving operations was rendered "clean cut" by further separation of water, applying Stokes' law[15] of settling velocities.

The products of the wet-separation process were treated with concentrated hydrochloric acid and then washed thoroughly on a filter with tap water until the filtrate would fail to change the color of blue litmus paper (as was done with the coarse fractions). The acid-free grains were washed with isopropyl alcohol to remove water and then with petroleum ether to remove alcohol. After the petroleum ether evaporated from the grains, they were dried in the same manner as the coarse fractions — by placing them in an oven at 350°C for 72 hours.

The finest of the seven end-product sand fractions, which passed through a 200 Tyler mesh sieve (opening = 74 microns) and was retained on a 325 Tyler mesh sieve (opening = 44 microns), was subjected to a Klein hydrometer

analysis[12] and found to contain particles as small as 24 microns in Stokes' diameter.

The sand used in the propane-flow experiments was made by blending the seven foregoing clean-cut fractions. In terms of a Tyler sieve analysis, the end-product blend contained, respectively, 11.0, 8.7, 11.0, 11.0, 12.1, 22.0, and 24.2 per cent of 14-28, 28-35, 35-48, 48-65, 65-100, 100-200, and 200-325 mesh grains.

A testing machine (for determining the tensile and compressive strengths of engineering materials) was used in the sand-packing operations, the flow tube being in a vertical position in the machine with the packing being done against the upstream end. The sand was introduced in 250-gram increments, each having the foregoing end-product grain size distribution. After each increment was put in the tube the sand was compressed under a compaction pressure of 1,000 psi with simultaneous jarring of the tube. In each instance the upper surface of the sand was ruffled slightly, before another increment was introduced, so that stratification discontinuities would be eliminated. The thermocouple junctions were buried in the sand, at selected distances along the tube, during the packing operation. The average porosity of the resultant column of sand was calculated to be 27.3 per cent.

Experimental Procedure

After the tube was packed and assembled, the homogeneous-fluid permeability distribution of the column of sand was determined with dry air, by application of standard test procedure. Over a period of several days this test was repeated twice and the permeability distribution was found to be unchanged, indicating that the column was stable. Moreover, the test was repeated again with all-liquid propane as the fluid medium, between the third and fourth two-phase flow experiments. The results agreed with those obtained in the dry-air flow tests.

Preparatory to two-phase flow experimentation the system (Fig. 2) was twice evacuated and purged with the test grade of propane gas. With the system filled with this propane gas at about 20 psia and room temperature, action was taken to introduce liquid propane. A high-pressure container (conventional "gas bottle") of the test grade of saturated liquid and gaseous propane was inverted, connected to the suction line on the pump, and elevated so that the saturated liquid propane would tend to gravitate into the system. Precautions were taken to remove air from the connecting line and a filter was assembled in this line to preclude entrance of foreign matter into the system. The needle valve (Fig. 2) at the downstream end of the flow tube then was closed and the pump used to transfer propane from the supply tank to the system. This operation was performed at room temperature and as the fluid pressure increased in the system, gaseous propane condensed. The maximum pressure was controlled by shutting off the pump and by appropriately actuating the accumulator diaphragms. This propane-transfer operation was completed when the propane-supply tank was disconnected from the pump and the system filled at room temperature with liquid propane with the accumulator diaphragms about midway between the upper and lower extremities of their vertical paths of travel.

The second operation performed in making the apparatus ready for two-phase flow experimentation, was to circulate the propane in the system, and simultaneously, to establish a predetermined air-temperature distribution in the duct enveloping the flow tube, to adjust the temperatures of the hot and cold baths as required, to withdraw propane from the propane-flow circuit, as necessary, with the accumulators, and to regulate the pump speed. In this operation, establishment of a predetermined pressure and temperature for the liquid propane entering the flow tube and establishment of a predetermined pressure or temperature for the gas-liquid mixture leaving the flow tube, fixed the necessary bath temperatures, the amount of propane to be withdrawn by the accumulator, and the pump speed.

As a first approximation a linear temperature distribution was established in the air duct, in the direction of propane flow. After steady-flow conditions were attained, temperature differences, between the air outside the flow tube and the propane inside, were measured. The air temperatures then were adjusted to match the propane temperatures. When steady-flow conditions again were attained, this temperature measurement and adjustment process was repeated. It was found that the inside and outside fluid-temperature distributions would remain coincident after two or three such adjustments and that little additional regulation of the pump speed and hot and cold bath temperatures, was necessary.

Finally, under conditions of steady flow, with no appreciable transfer of heat across the walls of the flow tube and with liquid propane entering the tube and a gas-liquid mixture of propane discharging from the tube, temperature and pressure distributions in the propane, in the direction of flow, were measured, as well as the total weight rate of flow of the propane. At the conclusion of each of the five experiments the propane in the system was vented to the atmosphere, with nitrogen from one of the tanks of nitrogen (Fig. 2).

EXPERIMENTAL AND THEORETICAL RESULTS

Pressure-Temperature Data and the Vapor-Pressure Chart

Fig. 3 depicts a segment of the normal (plane-surface) vapor-pressure curve for propane, plotted from data published by Sage, Schaafsma, and Lacey.[3] Experimentally obtained pressure and temperature data from the present two-phase propane flow experiments are super-imposed on this chart. Each experimental point shown represents the pressure and temperature measured at some transverse section in the sand-packed flow tube during two-phase flow experimentation.

As described previously, the flow would be essentially isothermal in the all-liquid flow portion of the system. All-liquid flow is reflected on the chart for each of the five experiments, by the points that are above the vapor-pressure curve and form a straight line parallel to the pressure axis.

It has been indicated further that gas-liquid capillary pressures and capillary-pressure gradients would be of negligible magnitude if experimentally measured liquid pressure-temperature data, pertaining to the two-phase flow portion of the tube, fell on the vapor-pressure curve. As the liquid propane was the wetting phase in the experiments, the experimental points on Fig. 3 represent liquid pressure-temperature data. With the exception of one or two points, data pertaining to the two-phase flow portion of the tube fall, within the limits of experimental accuracy, on the vapor-pressure curve. Accordingly, this method of analysis indicates that the magnitudes of capillary pressures and capillary-pressure gradients, are negligible.

Selection of Relative-Permeability Relations

Theoretical calculations of pressure distributions and weight rates of flow, as made with Equation (22), for comparison to experimental results, require that k_L/k and k_G/k be known as functions of pressure. These functions, evidently, may be determined indirectly from the proper independent relationship between k_L/k_G and k_L/k, considering that Equation (24) yields k_L/k_G as a function of pressure. Validity of the theory

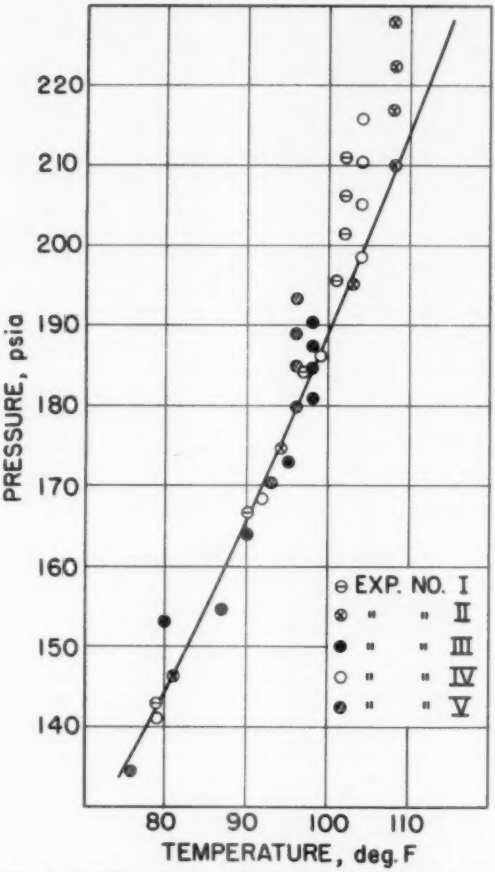

FIG. 3 — VAPOR-PRESSURE CURVE FOR PROPANE WITH SUPERIMPOSED PRESSURE-TEMPERATURE DATA FROM PROPANE-FLOW EXPERIMENTS.

must be assumed, however, if the necessary relationship between k_L/k_a and k_L/k is to be established with the test column of sand and two-phase fluid (propane), under conditions of adiabatic flow. Some other more appropriate course of action, therefore, is required to establish this relationship.

Based on the findings of Wyckoff and Botset,[5] the relative permeabilities of unconsolidated sands to either the wetting or nonwetting fluid depend almost entirely on the wetting-phase content of the sands. In this respect, those investigators experimented with a number of two-phase fluids and unconsolidated sands (ranging in homogeneous-fluid permeability from 17.8 to 262 darcys), and found that the relative permeabilities were practically independent of the test two-phase fluid and were influenced very little by the textural characteristics of the sands. When k_a/k and k_L/k data from all their experiments were plotted, on the same chart, against wetting-phase content, it was found that the plotted points, as a whole, indicated only one wetting-phase and one nonwetting phase relative-permeability curve, the scattering of the points about these curves being moderate and probably within the limits of experimental accuracy.

Consequently, it appears that the Wyckoff-Botset results could be used to plot a relationship between k_L/k_a and k_L/k that would describe reasonably well the relative-permeability characteristics of all unconsolidated sands. One could hardly expect this relationship to be exact, however, in describing the column of sand used in the propane-flow experiments as it had a homogeneous-fluid permeability of the order of one darcy. The foregoing findings, nevertheless, disclose that the relationship in question should represent a curve that lies in the vicinity of the Wyckoff-Botset curve.

Pursuant to this line of reasoning, data from one of the five propane-flow experiments were considered. The inlet temperature and pressure and the outlet pressure measured in this experiment (No. II), were used with the average curve through the Wyckoff-Botset results (Fig. 4) to calculate by Equation (22) the theoretical weight rate of flow and pressure distribution. The calculated results were compared to the experimental results and the curve shifted accordingly. The new curve was applied similarly and the curve-shifting procedure repeated until good agreement of calculated and experimental results was obtained. The final curve, located in this manner, is the propane-flow curve of Fig. 4. It falls well within the limits of experimental accuracy of the Wyckoff-Botset results. This propane-flow curve then was used in conjunction with Equation (22) to calculate total weight rates of flow and pressure distributions pertaining to the other four experiments.

In this conection the greatest experimentally-measured total weight rate of flow was approximately 100 per cent greater than the smallest total weight rate of flow, and the pressure and temperature distributions along the test column of sand varied widely among the five experiments. Thus, agreement of calculated and theoretical results for the four experiments used in testing the theory, would indicate that the propane-flow curve of Fig. 4 is independent of weight rates of flow and fluid properties, and, therefore, dependent only on the porous medium.

Substantiation of Theory

In making theoretical calculations the pressure and temperature of the all-liquid stream entering the column of sand and the pressure of the gas-liquid mixture discharging from the column, were considered as given. The problem was to find the corresponding pressure distribution and total weight rate of fluid flow.

In this respect, Table I presents a comparison of experimentally measured and theoretically calculated pressure distributions and total weight rates of flow. Substantiation of the theory is based on results pertaining to experiments I, III, IV and V, as data collected in experiment II were used as an aid in determining the propane-flow curve of Fig. 4.

Omitting experiment II, therefore, it is found that for experiment I the theoretical total weight rate of flow is 4.8 per cent greater than the corresponding experimental rate, and for experiments III, IV and V, the theoretical rates, respectively, are 5.4, 2.5 and 0.7 per cent less than the experimental rates. Similarly, the maximum difference between theoretical and experimental pressures for experiments I, III, IV and V are, respectively, 0.6, 0.6, 2.1 and 0.8 psi. In these experiments, in the same order, the total experimentally measured pressure differentials between the upstream and downstream ends of the sand column, were 67.9, 37.2, 74.6 and 58.8 psi.

Limitations of the experimental equipment and method of calculation disclose that the foregoing results (Table I) serve as a substantiation of the theory. Regarding the equipment, the test pressure gauge at the upstream end of the column of

sand was sensitive to one psi, the calibrations of the Flowrater indicated that that instrument could introduce errors up to about three or four per cent in the total weight rates of flow, and calibrations of the thermocouple circuit indicated that errors of the order of 1°F were likely to occur in temperature measurements. In connection with the method of calculation used, experiment II (Table 1) shows a theoretical weight rate of flow 0.3 per cent greater than the experimental rate and a maximum difference of 1.5 psi between theoretical and experimental pressures, the total drop in pressure in this experiment having been 81.5 psi between the upstream and downstream ends of the column of sand. Thus, as data from experiment II were used in finding the propane-flow curve of Fig. 4, differences between theoretical and experimental results for the other four experiments could be expected to be as great as those cited for experiment II. Homogeneous-fluid permeabilities measured for various increments of length along the sand column, were assumed, in the calculations pertaining to two-phase flow, to apply to the centers of the increments; hence, unknown local variations in homogeneous-fluid permeability would introduce errors. Finally, graphical methods of analysis were necessary in the calculations. It is estimated that these methods could introduce errors of the order of one or two per cent or more. Many of the viscosity data were obtained by extrapolation of curves.

Experimentally determined pressure distributions in the two-phase flow portion of the column of sand, are represented graphically in Fig. 5. This figure shows the ranges of pressure used in the experiments, indicates comparative pressure gradients and delineates the part of the column in which the fluid existed in two phases. The lefthand terminus of each of the curves defines the transverse section at which vaporization started, determined by a method of calculation described subsequently.

Details of an Application of Method Of Theoretical Calculation

The method used in making theoretical calculations is presented by developing theoretical results pertaining to experiment V, which was representative of all the experiments.

The pressure and temperature of the all-liquid propane stream entering the column of sand in this experiment were 193.2 psia and 96°F, respectively. With these data it is found[7] that the enthalpy of the compressed entering liquid is 24.4 Btu per lb of fluid flowing; thus, the constant enthalpy (H) of the process established (see Fig. 1).

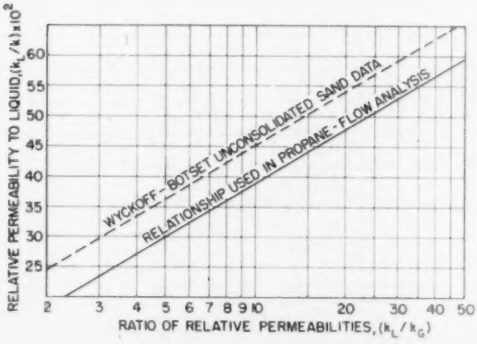

FIG. 4 — RATIO OF RELATIVE PERMEABILITIES AS FUNCTIONS OF RELATIVE PERMEABILITY TO LIQUID.

Table I—Comparison of Theoretical and Experimental Pressure Distributions and Total Weight Rates of Flow

Distance along column of sand, ft	Experiments									
	I		II		III		IV		V	
	Experimental and theoretical pressures, psia									
	Exp.	Theor.	Exp.	Theor.	Expt.	Theor.	Exp.	Theor.	Exp.	Theor.
0.000	210.8	210.8	227.8	227.8	190.3	190.3	215.6	215.6	193.2	193.2
0.833	206.0	205.8	222.1	222.2	187.3	187.6	210.2	210.4	188.5	189.0
1.669	201.4	200.9	216.6	216.7	184.6	185.0	205.0	205.4	184.8	184.9
2.510	195.5	194.9	209.7	209.9	180.7	180.6	198.5	199.1	179.6	179.7
3.351	184.1	184.3	195.1	196.6	173.1	173.2	186.2	186.9	170.2	169.4
4.187	166.5	166.9	174.6	175.7	164.0	164.0	168.4	167.5	154.7	154.2
4.570	156.9	157.0	164.5	163.8	159.8	159.2	158.8	156.7	146.4	145.9
4.778	149.8	150.1	155.7	155.3	156.4	156.2	149.7	149.1	140.4	140.3
5.028	142.9	142.9	146.3	146.3	153.1	153.1	141.0	141.0	134.4	134.4
	Experimental and theoretical total weight rates of flow, lb/hr									
	11.88	12.45	14.35	14.40	7.045	6.664	13.42	13.08	10.36	10.29

For saturated liquid propane an enthalpy of 24.4 Btu per lb corresponds to a pressure of 180.1 psia. At this pressure, therefore, vaporization started in the column (see Fig. 3).

To find the transverse section in the column, at which the pressure was 180.1 psia, it is noted first (Fig. 3) that the flow was essentially isothermal in the part of the column upstream from the place of initial vaporization. Moreover, the measured total weight rate of flow was 10.36 lb per hr, and at distances of 1.669 and 2.510 ft along the column, the measured pressures were 184.8 and 179.6 psia, respectively. In the indicated incremental length of sand column, the bulk cross-sectional area was 0.0237 sq ft and the homogeneous-fluid permeability 1.001×10^{-11} sq ft. Graphing of published data[2,3] discloses that the product of specific volume and absolute viscosity was 62.18×10^{-9} ft · sec for the liquid propane that was flowing between the transverse sections at which the pressures were 184.8 and 180.1 psia, respectively. Hence, application of Darcy's law in the conventional manner to homogeneous-liquid flow, gives 2.440 ft from the upstream end of the sand column as the distance to the transverse section where vaporization started (see Fig. 5).

Figs. 6 and 7 are, respectively, the pressure-function and integrated-pressure-function charts. These charts are necessary in determining the theoretical total weight rate of flow and pressure distribution. Data used in the preparation of these figures are entered in Table II and were developed as discussed below.

In Table II, the pressures at the upstream and downstream ends of the column, 193.2 and 134.4 psia, respectively, were measured; and, the pressure at which vaporization started (180.1 psia) was determined by the foregoing procedure. The pressure range from 180.1 to 134.4 psia was subdivided arbitrarily as shown in Column 1 so that data could be developed for constructing Figs. 6 and 7.

In the all-liquid flow portion of the sand column k_G/k obviously would have been zero and k_L/k unity; hence, for this part of the system $F(P)$ would be the reciprocal of $\mu_L \bar{v}_L$ (see Equations 21 and 22). This reciprocal was calculated to be 16.08×10^6 ft^{-1} · sec^{-1}, and the horizontal segment of the $F(P)$ vs P curve (Fig. 6) thereby became established.

Table II contains two entries of $F(P)$ for the pressure 180.1 psia. At the upstream side of the transverse section at which vaporization started, the fluid in the sand was entirely in the liquid state, and therefore, $F(P)$ for that section would be 16.08×10^6 ft^{-1} · sec^{-1} if it were approached from the upstream side. In accordance with the concept of an "equilibrium gas saturation,"[8] however, the pore space in the sand at the section in question would have contained a fixed quantity of static gas but no moving gas. This means that k_G/k would have been

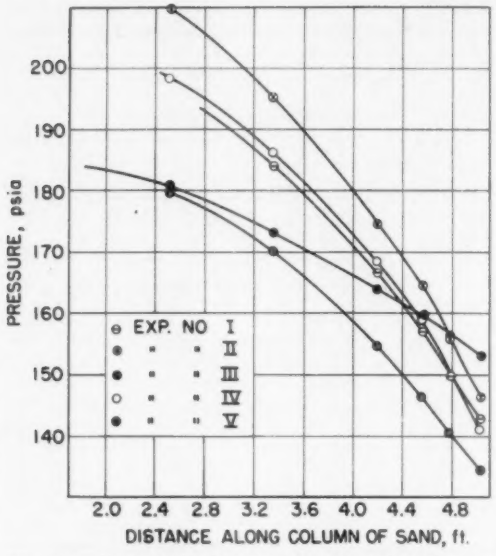

FIG. 5 — EXPERIMENTALLY-DETERMINED PRESSURE DISTRIBUTIONS IN TWO-PHASE FLOW PORTION OF TEST COLUMN OF SAND.

zero and k_L/k less than unity at the section. Hence, if the relative permeability of the liquid at the section is denoted by $(k_L/k)_e$, "the equilibrium permeability," and the section approached from the downstream side $F(P)$ for the section would be $(k_L/k)_e/(\mu_L\bar{v}_L)$.*

For unconsolidated sands, Wyckoff and Botset found that $(k_L/k)_e \simeq 0.79$. This value was used in the present analysis. A considerable error in this value would have no appreciable effect on the theoretically calculated results (Fig. 6).

With respect to the two-phase flow in the column of sand, published data[2,3] on saturated liquid and gaseous propane were used to plot $(\mu_L\bar{v}_L/\mu_G\bar{v}_G)$ and $(H-H_L)/(H_G-H_L)$ as functions of pressure. These plots were the source for data entered in Columns 2 and 3 of Table II. This information and application of Equation (24) led to the calculated values of k_L/k_G shown in Column 3. In turn, the data in Column 3 were used with the propane-flow curve of Fig. 4 to determine the corresponding relative permeabilities $(k_L/k$ and $k_G/k)$. Further use of the foregoing published data to plot $\mu_L\bar{v}_L$ and $\mu_G\bar{v}_G$ as functions of pressure, together with knowledge of k_L/k and k_G/k as functions of pressure, resulted in the entries in Columns 5 and 6. Corresponding entries in these columns were added to give the $F(P)$ entries in Column 7, which were used to construct Fig. 6.

Data for the construction of the integrated-pressure-function chart (Fig. 7) are entered in Column 7 of Table II. These data were obtained by dividing the total area under the curve in Fig. 6 into vertical strips and determining the area of each strip by application of either Simpson's rule or the trapezoidal rule. As the widths of the strips were governed by the pressure entries in Column 1, knowledge of their areas led directly to the entries in Column 7, which were used to construct Fig. 7.

To calculate the theoretical total weight rate of flow, Equation (22) was put in the form

$$W = \left[\sum_{i=1}^{i=8} \frac{A_i k_i}{\Delta x_i}\right] \cdot \int_{P_E}^{P_1} F(P)dP. \quad . \quad . \quad (29)$$

in which subscript i refers to the eight length increments into which the column was divided;* P_1 and P_E are the fluid pressures respectively at the upstream and downstream ends of the column.

The integral term in Equation (29) represents the total area under the curve in Fig. 6 and was calculated to be 706.42×10^6 lb · ft^{-3} · sec^{-1} (see Table II, Column 8). The term in brackets was calculated to be 2.473×10^{12} ft^{-2}. Hence, the theoretical total weight rate of flow was found to be 2.857×10^{-3} lb per sec or 10.29 lb per hr as compared to 10.36 lb per hr for the measured rate.

To find the theoretical pressure at the upstream end of the n-th increment ($n = 1, 2, 3, 4, 5, 6, 7$ or 8), the upper limits of the integral and summation in Equation (29) are changed to P_n. Under these conditions, the value of the integral may be calculated, as the theoretical weight rate of flow will be known. The calculated value of the integral, then, is used in conjunction with Fig. 7 to find P_n, the theoretical pressure at the upstream end of the n-th increment. Table I contains results determined in this manner.

*These eight incremental lengths were limited, respectively, to the following ranges of distance (Δx) along the sand column (measured in ft from the inlet face): 0.000 to 0.833, 0.833 to 1.669, 1.669 to 2.510, 2.510 to 3.351, 3.351 to 4.187, 4.187 to 4.570, 4.570 to 4.778, and 4.778 to 5.028. Starting at the upstream end of the column and proceeding downstream, the homogeneous-fluid permeabilities (k) of these increments were, respectively, 1.191, 1.244, 1.001, 0.8950, 0.8812, 0.9110, 0.7951 and 1.006 sq ft x 10^{-11}. Considered in the same order their average bulk cross-sectional areas (A) were, respectively, 0.02042, 0.02036, 0.02037, 0.02044, 0.02025, 0.02027, 0.02027, and 0.02027 sq ft.

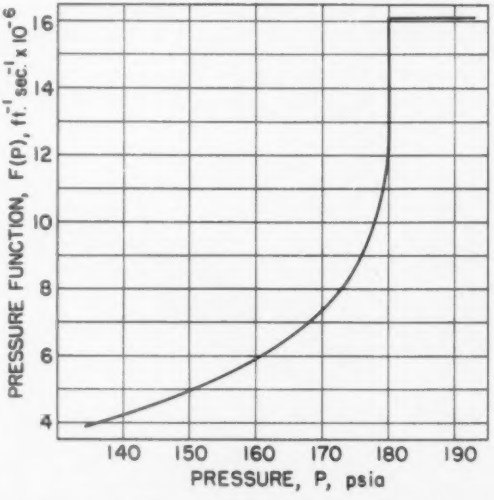

FIG. 6 — GRAPHIC REPRESENTATION OF PRESSURE FUNCTION (BASED ON THEORETICAL CALCULATIONS PERTAINING TO EXPERIMENT V).

*It is of interest to find that there would be a discontinuity in the fluid pressure gradient at the transverse section under consideration. Applying Darcy's law, the pressure gradient at the upstream side would be $-(W_{\mu_L\bar{v}_L}/Ak)$ and at the downstream side $-(W_{\mu_L\bar{v}_L})/[Ak(k_L/k)_e]$; hence the ratio of upstream to downstream gradients would be $(k_L/k)_e$.

CONCLUSION

The subject matter of this paper concerns the thermodynamic aspects of the steady flow of a single-component gas-liquid mixture, through porous media. The underlying, fundamental two-phase fluid-flow theory pertaining to this subject is developed, and laboratory experiments substantiating the theory are described.

It is pointed out in the paper that the thermodynamic process followed by oil-reservoir fluids while moving through porous underground rock formations is of significance in predictions of oil-reservoir behavior. Moreover, the flow of multi-component hydrocarbon fluids in these rocks is indicated to be intermediate between isothermal and adiabatic, but not susceptible to exact classification owing to a lack of necessary, detailed, heat-transfer data on subsurface rocks and fluid mixtures.

In an effort to perform the described experiments with the simplest appropriate two-phase flow system, it was decided that a single-component fluid should be used. This decision made isothermal flow impossible; hence, on the basis of the foregoing considerations, adiabatic flow was adopted for study.

In this respect, the experiments reported relate specifically to the steady adiabatic flow of propane in two phases through a horizontal column of sand, mounted in a specially designed apparatus. The propane, in all the experiments, entered the column entirely as a liquid, started to vaporize an appreciable distance downstream from the inlet, and then flowed in two phases throughout the remainder of the column.

Regarding the theory, the problem posed was to calculate the total weight rate of flow and the pressure distribution along the column of sand, for a given pressure and temperature of the all-liquid entering stream, a given pressure or temperature of the discharging gas-liquid mixture, and given sand and fluid characteristics. A comparison of theoretical and experimental results has been presented and discussed to show that the theory may be applied to solve this problem.

The theory, as developed herein, is premised on work done by O'Brien and Putnam.[1] The present paper shows, however, that equations developed by those investigators for calculating wetting-phase content and used by them in determining weight rates of flow and pressure distributions were not correct.

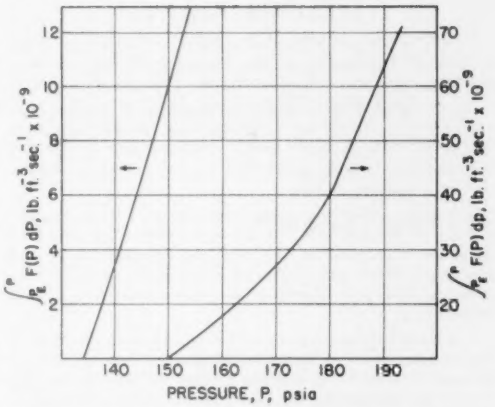

FIG. 7 — GRAPHIC REPRESENTATION OF INTEGRATED PRESSURE FUNCTION (BASED ON THEORETICAL CALCULATIONS PERTAINING TO EXPERIMENT V).

Attention is given in the present paper, moveover, to gas-liquid interfacial phenomena. The analyses made in this connection indicate that capillary pressures and their gradients are of negligible magnitude for single-component two-phase flow systems of the kind investigated.

Furthermore, the agreement among theoretical and experimental results indicates that the assumption of phase equilibrium, made in the development of the theory, is valid for the system studied.

In conclusion, the material offered in this paper should lead to a better understanding of oil-reservoir behavior in that the investigation pertains to the flow of a two-phase hydrocarbon fluid in sand. Substantiation of the theory suggests that it would be desirable to follow the reported work with a similar study of the two-phase flow of a multi-component hydrocarbon gas-liquid mixture through sand.

Table II — Data for Construction of Pressure-Function and Integrated-Pressure-Function Charts (Figs. 6 and 7, Respectively)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
P	$\frac{\mu_L \bar{v}_L}{\mu_G \bar{v}_G}$	$\frac{H - H_L}{H_G - H_L}$	$\frac{k_L}{k_G}$	$\frac{k_L/k}{\mu_L \bar{v}_L}$	$\frac{k_G/k}{\mu_G \bar{v}_G}$	$F(P)$	$\int_{P_E}^{P} F(P)dP$
psia	dimension-less	dimension-less	dimension-less	ft^{-1} . sec^{-1} x 10^{-6}	ft^{-1} . sec^{-1} x 10^{-6}	ft^{-1} . sec^{-1} x 10^{-6}	lb . ft^{-2} . sec^{-1} x 10^{-5}
134.4	0.3622	0.1067	3.032	3.477	0.4154	3.892	0.00
135	0.3631	0.1047	3.105	3.570	0.4174	3.987	3.57
140	0.3704	0.09386	3.576	3.872	0.4011	4.273	33.31
145	0.3779	0.08224	4.217	4.223	0.3784	4.601	65.26
150	0.3850	0.07038	5.086	4.610	0.3489	4.959	99.68
155	0.3916	0.05908	6.238	5.067	0.3181	5.385	136.92
160	0.3978	0.04762	7.956	5.575	0.2788	5.854	177.38
165	0.4037	0.03598	10.82	6.248	0.2331	6.481	221.79
170	0.4091	0.02417	16.52	7.152	0.1771	7.329	271.34
175	0.4137	0.01293	31.58	8.567	0.1122	8.679	328.57
180.1	—	0.00000	∞	12.71*	0.0000	12.71	403.08
180.1	—	"	"	16.08	"	16.08	403.08
193.2	—	"	"	"	"	"	706.42

*$(k_L/k)_e \doteq 0.79$ — from Wyckoff - Botset[5] results.

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REFERENCES

1. O'Brien, M. P., and Putnam, J. A.: "Some Problems of Horizontal Steady Flow in Porous Media." AIME T.P. 1349, *Petr. Tech.*, (July, 1941).
2. Sage, B. H., Schaafsma, J. G., and Lacey, W. N.: *Ind. Eng. Chem.*, (Nov., 1934), **26**, No. 11, 1218-1224.
3. Sage, B. H., and Lacey, W. N.: *Ind. Eng. Chem.*, (July, 1938), **30**, No. 7, 829-834.
4. Aboul-Seoud, Hassan: "Equilibrium Considerations in Two-Phase Flow of Hydrocarbons through Unconsolidated Sands." Unpublished Ph.D. thesis, University of California, Division of Mineral Technology, 1950.
5. Wyckoff, R. D., and Botset, H. G.: *Physics*, (Sept., 1936), **7**, No. 9, 325-345.
6. Botset, H. G.: *Trans.* AIME, (1940), **136**, 91.
7. Martinelli, R. C., Putnam, J. A., and Lockhart, R. W.: *Trans.* AIChE, (Aug. 25, 1946), **42**, No. 4, 681-705.
8. Edlefsen, N. E., and Anderson, A. B. C.: Thermodynamics of Soil Moisture, *Hilgardia* (A Journal of Agricultural Science, published by the California Agricultural Experiment Station), (Feb., 1943), **15**, No. 2, 142-146.
9. Calhoun, John C., Jr., Lewis, Maurice, Jr., and Newman, R. C.: *Trans.* AIME, (1949), **186**, 189.
10. Muskat, M.: *Physical Principles of Oil Production*, McGraw-Hill Book Co., Inc., New York, (1949), 311-321.
11. Lamb, Horace: *Hydrodynamics*, Dover Publications, 6th ed., New York, (1945), 597-599.
12. Klein, Alexander: "An Improved Hydrometer Method for Use in Fineness Determinations," ASTM Symposium on New Methods for Particle Size Determination in the Subsieve Range, Washington Spring Meeting, (Mar. 4, 1941).

DISCUSSION

By E. C. Babson, Union Oil Co. of California, Member AIME

Miller has succeeded in obtaining remarkable agreement between experimental results and analytical theory, indicating that phase equilibrium is attained very rapidly under the conditions of his experiments.

The relative permeability data used in calculating the pressure gradients, however, were not established for the sand column used in the experiments but were obtained by shifting Botset's K_g/K_o curve to reach an overall fit on one of the runs. The relation established in this manner was used in the calculations for all runs.

There is, therefore, a possibility that the agreement between theory and experiment is due to compensating errors. When consideration is given to the excellent agreement at each pressure tap for each run, it must be admitted that this possibility is remote, but it still exists and should be recognized.

AUTHOR'S REPLY TO MR. BABSON

Babson's comment regarding relative-permeability data is well taken. Perhaps this matter should have been discussed in more detail in the paper.

The paper includes a statement to the effect that validity of the theory must be assumed if the relationship between k_1/k_a and k_1/k is to be established with (and for) the test column of sand, under conditions of adiabatic flow with two-phase propane. The Wyckoff-Botset unconsolidated-sand data were utilized in the described manner, therefore, as a recourse.

If this procedure had not been followed, then the collection of independent relative-permeability data for the test sand column would have been necessary. Considering the high sensitivity of calculated weight rates of flow and pressure distributions to such data, it is evident that an independently-determined k_1/k_a vs k_1/k curve would most probably require shifting (within the limits of experimental accuracy) before an acceptable agreement of theory and experiment were obtained. As this shifted curve would have about the same theoretical significance as the propane-flow curve of Fig. 4, it too, would give rise to a remote possibility of an unsound agreement of theory and experiment. Accordingly, one concludes that no important gain would result from the collection of independent relative-permeability data. ★ ★ ★

TRANSIENT FLOW IN GAS TRANSMISSION LINES

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INTRODUCTION

The transient flow of gases in long pipe lines is a problem of industrial interest. The present discussion deals with the application of the conservation of momentum and material to the transient flow of gas in conduits which are long with respect to their diameter. Solutions of the resulting equations include consideration of variations in friction and specific volume of the fluid as functions of time and position along the conduit. The changes in state along the pipe line are established as a function of time. The methods proposed may be extended to other situations.

The flow of compressible fluids under steady conditions[1] has been considered in detail. Primary emphasis was placed on the development of simple means of taking into account the non-uniform flow[1] realized in long conduits under such conditions. Binder[2] discussed the essential differences between the flow of compressible and noncompressible fluids. Bonilla[3] proposed direct methods of solution for equations describing isothermal flow in long pipes. Similar considerations limited to steady flow have been discussed by Ruth.[4] Palsgrove[5] suggested a graphical means of solving specific problems relating to the flow of gases in conduits of uniform section. Some of the basic concepts of the flow of a compressible viscous fluid in straight tubes have been described by Kuo.[6] Problems of this type require knowledge of the equation of state of the fluid. In many cases it has been convenient to assume that the fluid follows the relationship ascribed to a perfect gas.

The treatment of unsteady flow of compressible fluids is less complete. This state of affairs results from the fact that the differential equations relating pressure and flow rate with time and position for unsteady flow are nonlinear in character.[7] Muskat and Wyckoff[8] presented an excellent treatment of the situation in laminar flow where inertia forces were not of controlling importance. Somewhat earlier Hurst[9] discussed the unsteady flow of fluids in petroleum reservoirs. Hetherington, MacRoberts, and Huntington[10] established experimentally the pressure distribution and accumulative flow rate of natural gas through an unconsolidated sand. Recently Joffe[11,12] considered the specific problem of the flow of natural gas in relatively long pipe lines for unsteady conditions with emphasis upon the economic feasibility of the storage of gas in such a reservoir. These discussions were based upon approximations of the partial differential equations applying to the conditions of flow. The results were descriptive of the physical situation and indicated the effectiveness of large pipe lines as cyclic storage facilities for natural gas. The advent of analog computers[13] has increased materially the practicality of solving nonlinear partial differential expressions. Several iterative numerical and graphical methods[14,15,16] have been developed to solve nonlinear equations. However, it appears that the pair of simultaneous nonlinear partial differential equations involved in problems of this nature are not directly susceptible to solution by presently available analog computer or formal iterative numerical techniques. Nevertheless, graphical analyses afford a means of obtaining data of engineering value without special equipment.

MATHEMATICAL CONSIDERATIONS

Since the length of the conduit is large in comparison to the cross section in the cases to be considered, it is possible to treat the characteristics of the flow as independent of position in the cross section of the conduit. This possibility follows since the energy connected with the velocity profile is small compared to that required to overcome the friction associated with its movement throughout the length of the line. Average values of the pressure, velocity, kinetic energy, momentum, and specific volume may be assigned to the fluid at any particular cross section. From a mathematical viewpoint this may be expressed in the following way for velocity:

$$u = u(\theta X) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The uncertainties introduced by such assumptions usually are negligible when the ratio of length to diameter is greater than the order of 1,000. On this basis a volume element may be considered to occupy the entire cross section of the conduit. Such an element is presented in Fig. 1.

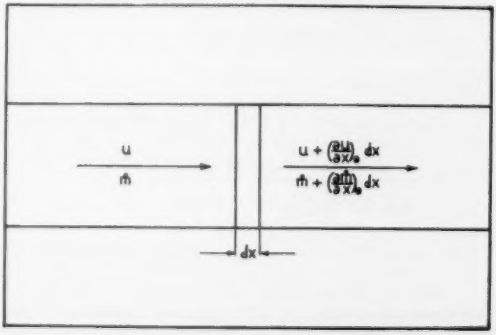

FIG. 1 — VOLUME ELEMENT IN A LONG PIPE LINE.

[1]References given at end of paper.
Manuscript received by the Petroleum Branch Oct. 27, 1950.

A material balance applied to the volume element yields the following expression for a conduit of cross-sectional area A:

$$\frac{\partial \sigma}{\partial \theta} + \frac{1}{A}\frac{\partial \dot{m}}{\partial X} = 0 \quad \ldots\ldots\ldots (2)$$

The foregoing equation represents the fact that the difference in the material entering and leaving a particular part of the pipe line in a given time is equal to the change in the quantity of material within the section of the pipe line under consideration.

A force balance upon the differential element of volume shown in Fig. 1, which is equivalent to assuming conservation of momentum, is given by the following equation:

$$\frac{1}{gA}\frac{\partial \dot{m}}{\partial \theta} + \frac{\partial}{\partial X}\left(P + \frac{\dot{m}^2}{g\sigma A^2}\right) + \frac{\tau \pi d}{A} = 0 \quad . \quad (3)$$

Following conventional practice,[11] the shear per unit length is empirically related to the conditions of flow and the friction factor in the following manner:

$$\frac{\tau \pi d}{A} = \frac{f}{2\sigma g}\frac{\dot{m}^2}{dA^2} \quad \ldots\ldots\ldots (4)$$

A combination of Equations (3) and (4) yields the expression:

$$\frac{1}{gA}\frac{\partial \dot{m}}{\partial \theta} + \frac{\partial}{\partial X}\left(P + \frac{\dot{m}^2}{g\sigma A^2}\right) + \frac{f\dot{m}^2}{2\sigma g d A^2} = 0 \quad . \quad (5)$$

For the majority of conditions encountered in the transient flow of natural gas in long pipe lines the inertia effects are small, and it is believed that except in special circumstances where numerous large changes in velocity are encountered the forces associated with the acceleration of the flow can be neglected without introducing appreciable error. In the examples to be considered the neglect of these inertia terms did not introduce errors greater than 0.8 per cent in the reported values of pressure. If the inertia effects are neglected, Equation (5) simplifies to the following form:

$$\frac{\partial P}{\partial X} + \frac{f\dot{m}^2}{2\sigma g d A^2} = 0 \quad \ldots\ldots\ldots (6)$$

The evaluation of Equations (2) and (6) requires a knowledge of the relationship between pressure and specific weight of the gas. In the present instance it is not necessary to employ a complex equation of state and the following expression appears adequate for the present discussion:

$$\sigma = \frac{P}{bT - P\underline{V}} = \frac{P}{bT - PB} \quad \ldots\ldots\ldots (7)$$

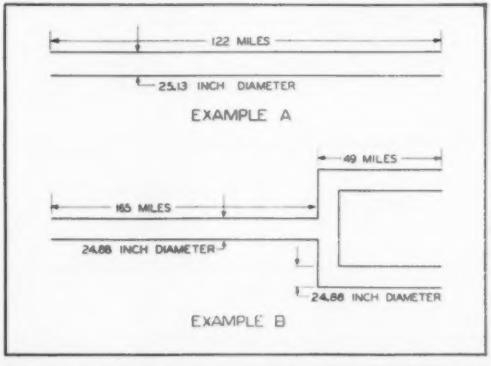

FIG. 2—SCHEMATIC DIAGRAM OF PHYSICAL SITUATION FOR EXAMPLES A AND B.

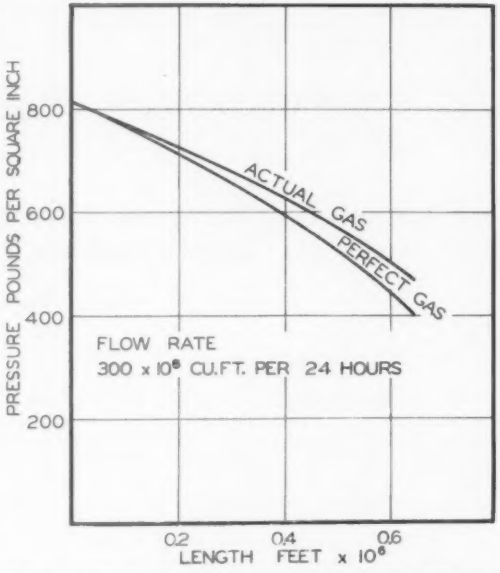

FIG. 3 — PRESSURE AS A FUNCTION OF POSITION UNDER STEADY-STATE CONDITIONS IN EXAMPLE A.

Or, neglecting terms of order $(PB/bT)^2$ this may also be written in the form:

$$\sigma = \frac{1}{bT}\left(P + \frac{B}{bT}P^2\right) \quad \ldots\ldots (8)$$

The residual volume $\underline{V}$ has been considered a constant for the range of pressure of interest as is indicated in the third term of Equation (7) and Equation (8).

Table I — Description of the Situation

	Example A	Example B
Length of pipe line,		
miles	122	214*
feet	0.6442×10^6	1.131×10^6
Diameter of conduit, feet	2.094	2.072
Temperature, degrees F	60	60
Upstream pressure, psi	815	
Flow rate, cu ft/24 hr	300×10^6**	300×10^6
Composition of gas, mole fraction		
methane	0.94	
ethane	0.04	
propane and heavier	0.02	
Average molecular weight	17.28	19.79
Viscosity of gas, lb, sec/sq ft	0.2799×10^{-6}	0.2108×10^{-6}
Residual specific volume, cu ft/lb	0.05471	0.0495
Constants of Equations (9) and (10)		
a	0.019724	
c	0.07534	0.11754
n	0.1205	0.1454

*The line is 214 miles in length with the final 49 miles made up of a pair of conduits, each of the same cross section as the single conduit making the preceding 165 miles of the system.
**Measured at 60°F, 14.73 psia.

SPECIAL CONDITIONS

The remaining portion of this discussion is concerned with two special problems which differ materially as to the physical situations. The units of measure used in the two examples have been chosen somewhat differently. However, the force-length-time system of dimensions has been employed. The situation associated with each of the pipe lines is presented in a part of Table I, and in Fig. 2 is depicted a diagrammatic sketch of their arrangement.

The friction associated with the flow was established from the correlation of Pigott,[15] which is based in part upon the experimental work of Nikuradse.[16] The friction factor is empirically related to the Reynolds number in the following way:

$$f = cRe^{-n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

It is assumed that viscosity is independent of pressure over the range of conditions encountered. If the diameter of the line is uniform, it follows that the friction factor becomes a single-valued function of the weight rate of flow as is indicated below.

$$f = a\dot{m}^{n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Further consideration of the problem necessitates treatment of a specific set of boundary conditions and the discussion will be applied to each situation separately.

Example A

The physical situation involved in this problem is set forth in a part of Table I. It is desired to determine the variation of pressure with respect to time at the exit of a pipe line 122 miles in length when flow suddenly is curtailed at the inlet while gas is withdrawn continuously at the outlet at a constant rate of 300 x 10⁶ cu ft per day.*

The viscosity of the gases employed is reported in a part of Table I and is based upon experimental measurements of viscosity of similar gases.[4] In Example A the friction factor is related to the weight rate of flow by the following equation:

$$f = 0.019724\dot{m}^{-0.1295} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

The associated values of the constants of Equations (9) and (10) are shown in a part of Table I. In this instance the specific volume at 60°F may be expressed in terms of the pressure by the relation:

$$V = \frac{1}{\sigma} = \frac{322.72}{P} - 0.05471 \quad . \quad . \quad . \quad . \quad . \quad (12)$$

A combination of Equations (6), (7), and (10) followed by appropriate integration results in the following expression for steady flow:

$$\frac{P_2 - P_1}{B} + \frac{bT}{B^2} \ln \frac{bT/B - P_2}{bT/B - P_1} = \frac{a\dot{m}^{(2-n)}}{2gdA^2}(X_2 - X_1) \quad . \quad (13)$$

In the case of a perfect gas where the residual volume, *i.e.*, the assumed constant B is zero, Equation (13) reduces to a simpler form.

$$P_1^2 - P_2^2 = \frac{abT\dot{m}^{(2-n)}(X_2 - X_1)}{gdA^2} \quad . \quad . \quad . \quad . \quad (14)$$

The application of the specific volumetric data of Equation (12) in Equation (13) and the substitution of the boundary conditions listed in Table I yield the following expression for the distance along the pipe line under steady conditions of flow as a function of the prevailing pressure:

$$X - X_1 = \frac{-4.2044 \times 10^6}{(0.019724)\dot{m}^{1.8705}} \left\{ 815 - P + 13582 \log_{10} \frac{5083.7}{5898.7 - P} \right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

In Fig. 3 is shown the pressure as a function of position along the pipe line for a flow rate of 300 x 10⁶ cu ft per 24 hr.

In the case of unsteady flow both Equations (2) and (6) must be satisfied. Under these circumstances the pressure gradient may be expressed in a slightly different form from that originally employed in Equation (6).

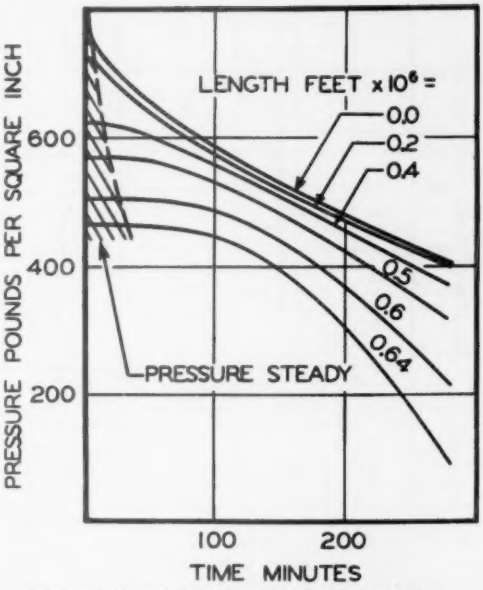

FIG. 5 — VARIATION IN PRESSURE WITH TIME FOR EXAMPLE A.

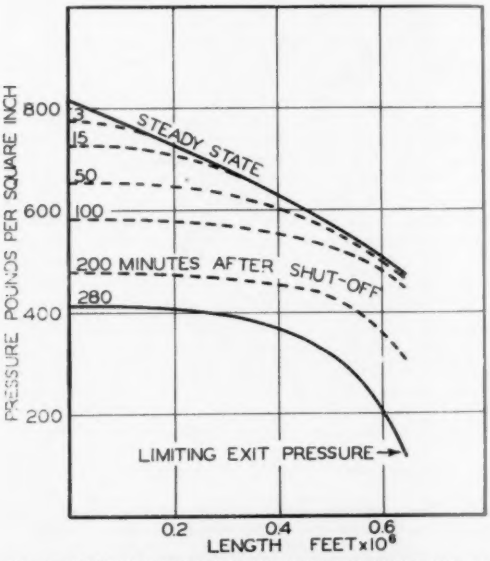

FIG. 4 — PRESSURE DISTRIBUTION FOR UNSTEADY CONDITIONS IN EXAMPLE A.

*All volumetric measurements relating to the quantity of gas correspond to a temperature of 60°F and a pressure of 14.73 psia. The indicated volumetric rate corresponds to 160.7 lb of gas per second.

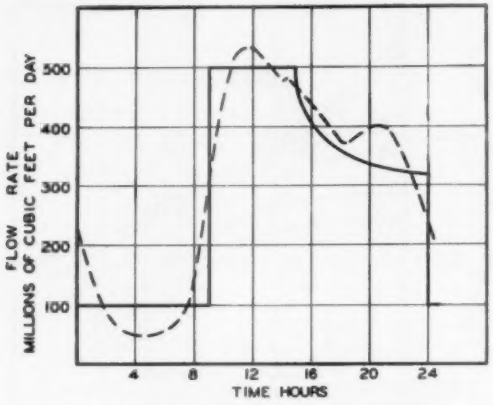

FIG. 6 — VARIATION IN OUTPUT RATE FOR EXAMPLE B.

$$\frac{\partial P}{\partial X} = \frac{bT}{P}\left(\frac{PB}{bT} - 1\right)\frac{a}{2gdA^2}\dot{m}^{(2-m)} \quad . \quad . \quad . \quad (16)$$

The change in pressure with respect to time may be obtained directly from Equations (2) and (7).

$$\frac{\partial P}{\partial \theta} = -\frac{bT}{A}\left(\frac{PB}{bT} - 1\right)^2 \frac{\partial \dot{m}}{\partial X} \quad . \quad . \quad . \quad . \quad . \quad (17)$$

Both Equations (16) and (17) are applicable at all points in the pipe line. An iterative graphical procedure was employed to construct a solution for these equations which satisfied the required boundary conditions. The details of a similar graphical operation are set forth in the latter part of this paper.

The situation at various times after the flow is interrupted is shown in Fig. 4 upon the assumption of perfect gas behavior. It is apparent that during the initial period after shutoff there has been no change in the downstream pressure. Fig. 4 also depicts the pressure distribution after an elapse of 280 min. At this time the exit pressure has decreased to 115 psi, which was considered to be the minimum pressure feasible for the operation of the transmission line. Fig. 5 shows the estimated variation in the pressure with respect to time at various points along the pipe line. Little or no change in pressure at the exit is obtained for a period of about 45 min. Subsequent to that interval, the exit pressure decreases at an increasing rate until the effectiveness of the line as a storage facility is substantially exhausted after about 280 min.

Example B

The physical situation considered in this example is markedly different from that of the preceding one. The gas entered a pipe line 214 miles in length which was made up of 165 miles of single conduit and 49 miles of two parallel conduits of the same cross section as that of the first part of the line. This design was employed to increase the storage capacity of the system under transient conditions. The system was operated at an input rate of 300 x 10^6 cu ft per 24 hr. The output rate of flow varied as indicated in Fig. 6. In the interest of ease of computation the continuous distribution indicated by the dotted curve was simplied to the discontinuous relation shown by the full line. It was desired to determine the pressure distribution in the pipe line during a 24-hr period corresponding to the withdrawal rates indicated in Fig. 6 while the input flow rate remained constant at 300 x 10^6 cu ft per day. The total withdrawal per 24 hr was 300 x 10^6 cu ft.

In this instance the specific weight of the gas at 60°F is related to the pressure in the following way:

$$\sigma = 0.003547(P + 0.000176\,P^2) \quad . \quad . \quad . \quad (18)$$

The friction factor was related to the Reynolds number in accordance with Equation (9).

$$f = 0.11754\,\mathrm{Re}^{-0.1482} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

A combination of the foregoing isothermal equation of state and the expression for friction with Equations (2) and (6) leads to the following expressions in which the distance is expressed in miles, the time in hours, and the flow rate in millions of cubic feet per day:*

$$\frac{\partial}{\partial \theta'}(P + 0.000176\,P^2) + 33.014\frac{\partial \dot{V}'}{\partial X'} = 0 \quad . \quad . \quad (20)$$

$$\frac{\partial}{\partial X'}(P^2 + 0.0001173\,P^3) + 0.10788\,\dot{V}'^{1.8518} = 0 \quad . \quad (21)$$

Under steady-state conditions Equation (20) vanishes and Equation (21) may be integrated to yield:

$$[P^2 + 0.0001173\,P^3]_{P_2}^{P_1} = 0.10788\,\dot{V}'^{1.8518}(X_1 - X_2) \quad . \quad (22)$$

In Fig. 7 is presented the pressure distribution in the pipe line for two limiting conditions of steady flow rates. The first is associated with the maximum entrance pressure of 970 psi which yields an exit pressure of 518 psi. The second condition is related to the minimum acceptable exit pressure of 265 psi which necessitates an entrance pressure of 870 psi. These conditions correspond to the limiting range of steady operation which permits the transmission of 300 x 10^6 cu ft of gas per

*Measured at 60°F, 14.73 psia.

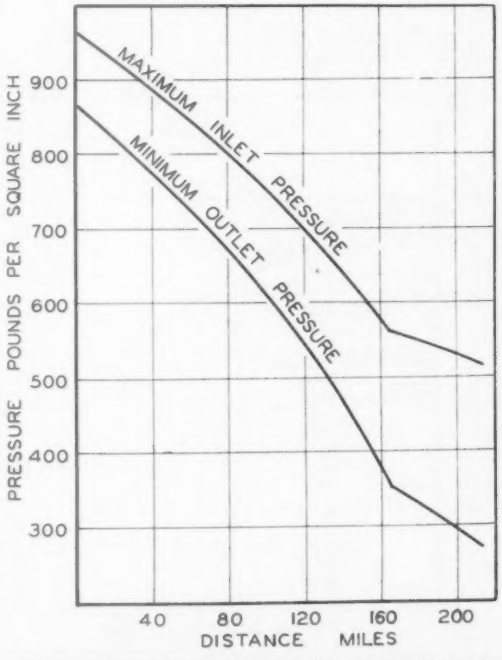

FIG. 7 — PRESSURE DISTRIBUTION FOR STEADY FLOW CONDITIONS IN EXAMPLE B.

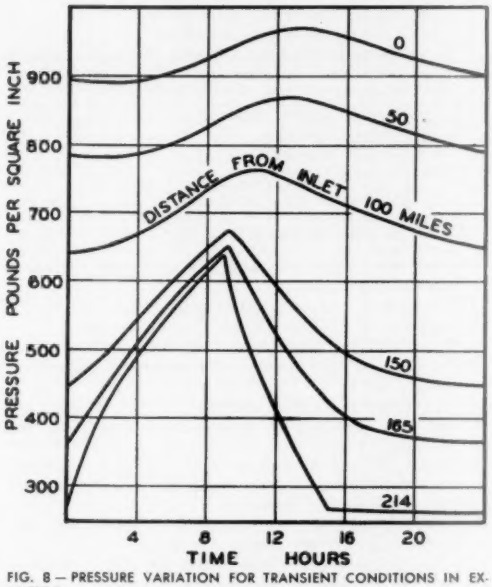

FIG. 8 — PRESSURE VARIATION FOR TRANSIENT CONDITIONS IN EXAMPLE B.

24 hr. It was assumed in the last 49 miles of the conduit that the flow was divided equally between the two conduits.

The discontinuity in the slope of the pressure distribution curves in Fig. 7 corresponds to the point where the flow divides between the two identical conduits. The transition from steady to cyclic exit conditions involved secondary transients which were also completely dissipated by the end of the first cycle.

The distribution of pressure in the pipe line is depicted in Fig. 8 as a function of time and position. At the entrance to the conduit a cyclic variation in pressure from 890 to 970 psi is obtained during a given 24-hr period. At the exit the pressure changes from a minimum value of 270 to a maximum of 640 psi. The discontinuous nature of the slope of this curve results from the assumption shown in Fig. 6 of discontinuous changes in the demand rate of flow. In actual practice the rate of flow would not change discontinuously and the rate of change of pressure with time at the exit would be continuous. The pressure distribution in the pipe line for several different periods in the cycle constitutes Fig. 9.

A GRAPHICAL METHOD OF SOLUTION

The pattern of graphical operations used in constructing solutions for the examples described in this paper was devised only after effort had been expended in attempting to apply other approaches. An explanation of the step-wise solution employed in connection with Equations (20) and (21) follows:

1. Consider the pipe line at some known conditions throughout its length. In the present case initial conditions corresponding to steady-state flow of 300 x 10^6 cu ft per day were chosen.
2. Permit the output flow to vary in accordance with the prescribed cycle and graphically construct a family of curves representing $\dot{V}'$ vs X for various arbitrarily chosen times. This step appears somewhat difficult, but in practice it may be accomplished crudely by using "intuitive guesses" to approximate the behavior of the system.
3. With the aid of Equation (21) compute $P^2 + 0.0001173\,P^2$ for several values of X. This may be accomplished by graphical integration of $\dot{V}'^{1.5286}$ with respect to X.
4. Plot curves representing the quantity $P + 0.000176\,P^2$ for the range in values of X. Graphical integration of these curves with respect to X will determine the total gas content of the pipe line at each of the arbitrarily chosen times adopted in Step 2.
5. Compute from the input and output flow rates the time corresponding to each curve in Steps 2 and 4 by correlating the cumulative difference in these flow rates with the net change in gas content of the pipe line.
6. Cross plot $P + 0.000176\,P^2$ with respect to time and differentiate the resulting curves with respect to time.
7. Compute $\dfrac{\partial \dot{V}'}{\partial X}$ with the aid of Equation (20) and integrate graphically plots of this quantity with respect to X so as to obtain a new set of relations between flow rate, position, and time.

The process beginning with Step 3 may now be repeated to obtain a second approximation. In this example the convergence was found to be sufficiently rapid so that only three iterations of the above-described steps were required to yield a substantial convergence. In this manner, starting from the assumed initial conditions, computations for the second example in this paper were carried through two complete cycles, corresponding to a period of 48 hr. It was found that the pressure distribution at the end of the first cycle did not differ significantly from that at the end of the second cycle. It was concluded, therefore, that the assumption of an arbitrary initial condition for the pipe line did not materially influence the behavior of the system after the first cycle.

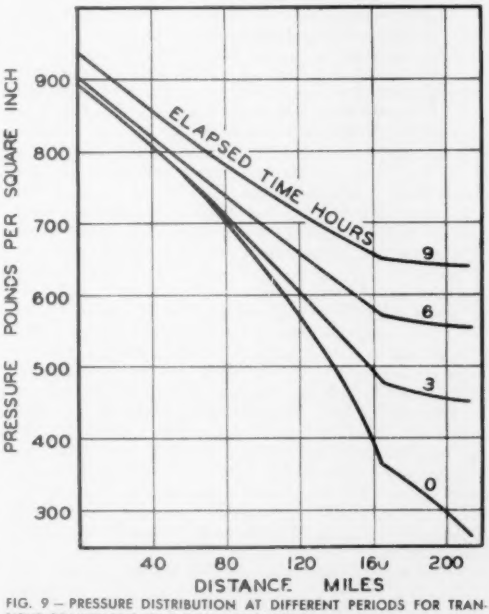

FIG. 9 — PRESSURE DISTRIBUTION AT DIFFERENT PERIODS FOR TRANSIENT CONDITIONS OF FLOW IN EXAMPLE B.

SUMMARY

The foregoing Examples A and B demonstrate the fashion in which the partial differential equations describing the conservation of momentum and material may be applied to the prediction of the pressure distribution in long pipe lines carrying gas under transient conditions. Example A considers a problem wherein the flow at the entrance to the pipe line is interrupted and the second predicts the cyclic pressure distribution to be anticipated in a gas transmission line with a constant input and a cyclic demand rate.

The graphical procedures outlined here for solving these problems may be expected to yield satisfactory results for wide variations in flow conditions, provided situations involving shock waves and supersonic flow do not arise.

ACKNOWLEDGMENT

The authors are grateful to The Stearns-Roger Manufacturing Co., to the Southern Counties Gas Co. of California, and to the Southern California Gas Co. for financial support in the study of Examples A and B, respectively. V. J. Berry assisted in the assembly of the manuscript.

NOMENCLATURE

A — cross-sectional area, sq ft
a — constant defined in Equation (10)
B — constant defined in Equation (7)
b — pecific gas constant
c — onstant defined in Equation (9)
d — liameter of pipe line, ft
f — friction factor
g — acceleration resulting from gravity, ft per sec per sec
$\dot{m}$ — total weight rate of flow, lb per sec
n — exponent of Equation (9)
P — pressure, psi
T — thermodynamic temperature, °R
u — velocity, ft per sec
$\underline{V}$ — residual specific volume, cu ft/lb
$\dot{V}'$ — volumetric flow rate, cu ft x 10^6 per 24 hr
V — pecific volume, cu ft/lb
X — distance along pipe line, ft
X' — distance along pipe line, miles
τ — shear at boundary of flowing stream, lb per sq ft
θ — time, sec
θ' — time, hr
φ — specific weight, lb per cu ft
ln — natural logarithm
log — Briggs' logarithm
Re — Reynolds number

REFERENCES

1. Rouse, H.: *Fluid Mechanics for Hydraulic Engineers*, McGraw-Hill, (1938).
2. Binder, R. C.: *Chem. and Met. Eng.*, (1944), **51**, 99.
3. Bonilla, C. F.: *Ind. Eng. Chem.*, (1939), **31**, 618.
4. Ruth, B. F.: *Ind. Eng. Chem.*, (1939), **31**, 985.
5. Palsgrove, G. K.: *Rensselaer Polytechnic Instit. Bull.*, (1932), No. 37.
6. Kuo, Y. H.: *Jour. Math. and Phys.*, (1943), **22**, 13.
7. Fry, T. C.: *Elementary Differential Equations*, D. Van Nostrand, (1929).
8. Muskat, M., and Wyckoff, R. D.: *The Flow of Homogeneous Fluids Through Porous Media*, McGraw-Hill, (1937).
9. Hurst, W.: *Physics*, (1934), **5**, 20.
10. Hetherington, C. R., MacRoberts, D. T., and Huntington, R. L.: *Trans.* AIME, (1942), **146**, 166.
11. Joffe, J.: *Chem. Eng.*, (Nov., 1949), **56**, 112.
12. Joffe, J.: *Chem. Eng.*, (Aug., 1949), **56**, 130.
13. McCann, G. D., Wilts, C. H., and Locanthi, B. N.: *Proc. Inst. Radio Engrs. Trans.*, (1949), **37**, 954.
14. Scarborough, J. B.: *Numerical Mathematical Analysis*, The Johns Hopkins Press, (1930).
15. Southwell, R. V.: *Relaxation Methods in Engineering Science*, Oxford University Press, (1940).
16. Southwell, R. V.: *Relaxation Methods in Theoretical Physics*, Oxford University Press, (1946).
17. Daugherty, R. L.: *Hydraulics*, McGraw-Hill, (1937).
18. Pigott, R. J. S.: *Mech. Eng.*, (1933), **55**, 497.
19. Nikuradse, J.: *VDI*, Forschungsheft 356 (1932).
20. Sage, B. H., and Lacey, W. N.: *Trans.* AIME, (1938), **127**, 118.

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NOMINEES FOR AIME OFFICES, 1952

Clayton G. Ball, chairman of the Nominating Committee for 1952 Officers, has announced nominations for president, president-elect, vice-president and directors for 1952. As provided in Article IX of the by-laws, 25 members or associate members may sign and transmit to the secretary's office prior to Sept. 1 "any complete or partial ticket of nominees," should they wish other candidates to be considered. In such instance, a letter ballot will be forwarded to all members in good standing in the United States, Canada and Mexico, tabulating both the official ballot and any supplementary nominations. If no nominations are received, no letter ballot will be printed, and nominees on the official ballot shall be declared duly elected at the meeting of the Board of Directors of the Executive Committee in November.

FOR PRESIDENT

MICHAEL L. HAIDER attended the University of Southern California and Stanford University, from which he was graduated in 1927 with a BA degree in chemistry. He worked for the Pacific Portland Cement Co., Pan-American Petroleum Co., Richfield Oil Co., and the Carter Oil Co., before joining the Standard Oil Development Co. in 1938 as manager of production engineering and research. In 1945 he became executive assistant in the producing department of Standard Oil Co. (New Jersey). In 1946 he was transferred to Imperial Oil Ltd., Canadian affiliate, with headquarters in Toronto. He is currently a vice-president and member of the board of directors. Haider was chairman of the Publications Committee of the Petroleum Division for several years. He was chairman of the Division in 1945, and has held numerous AIME committee posts. He is now a director of the Institute.

FOR PRESIDENT-ELECT

ANDREW FLETCHER, president of St. Joseph Lead Co., was born in 1895 in New York, N. Y., to which his paternal grandparents had come from Scotland in 1825. He attended Hill School and the Sheffield Scientific School, Yale University, where he received the PhB degree in mechanical engineering. In 1949 the University of Missouri conferred upon him an honorary degree of Doctor of Engineering. Fletcher has been treasurer of AIME since 1944. He is also president of Mine La Motte Corp., and Bonne Terre Farming and Cattle Co.; vice-president of Missouri-Illinois Railroad Co.; and director of the American-Hawaiian Steamship Co.

FOR VICE-PRESIDENTS

OLIVER B. J. FRASER, assistant manager of the Development and Research Division of the International Nickel Co., New York, N. Y., is a past chairman of the New York Section and has served on the following AIME committees: Ways and Means, Mining and Metallurgy (as chairman), President's Advisory, Nominations for 1951 AIME Officers (as chairman); Auxiliary Publications Committee of the Metals Division (as chairman), and Program Committee, IMD. He is the author of many publications, including several AIME technical papers. Fraser was born at Brockville, Ont., in 1885, and received the degree of BSc at Queen's University.

JAMES BAIN MORROW, vice-president of Pittsburgh Consolidated Coal Co., was awarded the Erskine Ramsey Gold Medal at the 1950 AIME Annual Meeting. He was born in Halifax, Nova Scotia, in 1886, and studied mining engineering at Dalhousie University. He has figured prominently on many committees of the AIME, and has been chairman, vice-chairman and Executive Committee member of the Coal Division. Many of his technical papers on the cleaning, sampling and preparation of coal have been published by AIME. In 1944 he received the Percy Nichols Award.

FOR DIRECTORS

C. HARRY BENEDICT served as a director of AIME from 1945 to 1950 and as vice-president from 1948 to 1950. He was born at Pittsburgh, Pa., in 1876 and graduated from Cornell University in 1897. Immediately after graduation he became affiliated with Calumet and Hecla Consolidated Copper Co., and remained with this company until his retirement in 1948. Benedict developed the ammonia leaching process for recovery of copper from waste sand (tailing). He is writing a history of the company which will be published late this year.

RUSSELL B. CAPLES was graduated from the Missouri School of Mines in 1910. Caples joined the Federal Mining and Smelting Co. in Idaho after graduation. He soon entered the employ of the Anaconda Copper Mining Co., where he assisted in the development of the electrolytic zinc process and the basic process for the Anaconda phosphate plant. In 1918 he became superintendent of the Great Falls, Mont., plant., and was named manager in 1941. He has served on a number of committees of the Extractive Metallurgy Division of AIME, and is now a member of the Advisory Committee on Zinc of the Defense Minerals Administration.

THEODORE BENTON COUNSELMAN received the Engineer of Mines degree from Columbia University. He soon entered the ore dressing industry, and worked with various companies. Entering the equipment sales field, he joined The Dorr Co. as manager of the Central Division in Chicago. He is now in charge of exploiting the company's newest development. Counselman has been chairman of the Chicago and New York sections, chairman of the Milling Methods Committee, vice-chairman of the Blast Furnace Coke Oven and Raw Materials Committee of the Iron and Steel Division, and has served on a number of other committees. He is currently chairman of the national Membership Committee.

THOMAS L. JOSEPH is now chairman of the Iron and Steel Division. He was born in Adamsville, Utah, in 1894, and received an MA degree from the University of Utah. He was employed by the U. S. Bureau of Mines' North Central Experiment Station in Minneapolis, and in 1936 became head of the Department of Metallurgy, Minnesota School of Mines and Metallurgy, where he is now assistant dean of the Institute of Technology. During World War II he was a member of the War Metallurgy Committee. He received the J. E. Johnson, Jr., Award in 1927 and the Richard W. Hunt Medal and Prize in 1937, and was Howe Lecturer for 1946.

CARL ERNEST REISTLE, JR., received a BS degree in chemical engineering from the University of Oklahoma in 1922. He worked as a petroleum chemist for the U. S. Bureau of Mines at Bartlesville, Okla., and Laramie, Wyo. In 1933 he became chairman of the East Texas Engineering Association, aiding in the establishment of conservation regulations. Since 1936 he has been with Humble Oil and Refining Co., and is now a member of the board and manager of the Production Department, located in Houston, Tex. During World War II he served as technical advisor for District III of the Petroleum Administration for War, and as national vice-chairman of the Oil Industry Advisory Committee for the OPA. ★ ★ ★

Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 408 Trinity Universal Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to the positions coded Y5532, Y5531, and Y5480 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

POSITIONS

♦ Engineers (a) Petroleum engineer for field operations, 25-35, with degree in petroleum engineering or equivalent and about three to five years' experience. (c) Division safety supervisor, 30-45, graduate, preferably mechanical, with five years' experience in petroleum, drilling and production safety supervision. (d) Junior engineers — petroleum, recent petroleum engineering graduates, capable of developing under training. Location, Peru, S. A. Y5532.

♦ Engineers. (a) Equipment and cost engineer, about 30, with petroleum engineering degree and about five years' experience. (b) Production engineer — petroleum, 25-40, with about four years' experience. (c) Reservoir engineer, 25-40, with about five years' reservoir engineering experience. (e) Drilling engineer, 25-35, with degree in petroleum engineering and about three years' experience. Location, Colombia, S. A. Y5531.

♦ Sales engineer, about 30, mechanical graduate, with some sales experience, for sale of industrial oil to paper mills, automotive manufacturers, heavy industry, etc., for major oil company. Location, Wisconsin. Y5480.

♦ Applications now being received from petroleum, chemical or mechanical engineers with PhD degrees and petroleum reservoir engineering experience for teaching positions on the petroleum engineering staff of a Southwestern institution. Salary based on background. Initiative essential. Interviews during July and September. Appointments effective September 1. Consulting and research encouraged. Send recent photograph with data. Code 531.

PERSONNEL

♦ Engineer, petroleum production, registered, presently employed, desires responsible position with aggressive independent or small producing company. Twelve years' experience mid-continent area all phases of production, specializing water flooding. Age 32, married. Code 150.

♦ August graduate in petroleum engineering, MS degree. Age 22, single, nonveteran, available August 10 for employment. About two years' non-engineering field and office experience. Will work anywhere. Code 151.

♦ Available petroleum engineer - production superintendent; 20 years' experience in drilling, production and secondary recovery. Code 147. ★ ★ ★

Economic Aspects

Continued from Page 16, Section 1

force corporations to withhold 20 per cent of all wages, and pay that amount withheld direct to the government as taxes.

One of the principal attacks in the general trend of nationalization or socialization has been against the oil and gas industry, for through the control of fuel and energy everything else can be controlled. Once private industry has lost control of oil and gas, the private control of other industries must likewise eventually be lost.

The position of oil in world affairs is not apt to be disturbed except by unwise legislation, but by such legislation the capital of the oil industry can easily be taxed away and the present bountiful supply reduced to an actual shortage which thereby might well permit the government to take over.

The chief weapon of attack on the oil business has been through the elimination or reduction of the depletion allowance granted to the oil industry before determination of the net income subject to taxes. In the present session of Congress, the Treasury Department sought to reduce the present rate of depletion, which is 27½ per cent of the gross income, to 15 per cent, and previously the Treasury had endeavored to have depletion eliminated entirely. Fortunately, due to the understanding of Congress of the subject, the Treasury Department has so far not prevailed, but the attack continues.

Oil, when once found, produced and consumed, cannot be replaced. Basically, it is only liquid energy and must be consumed or destroyed in order to be utilized. ★ ★ ★

Proposed for Membership, Petroleum Branch

Total AIME membership on January 31, 1951, was 17,228; in addition, 4,613 Student Associates were enrolled.

ADMISSIONS COMMITTEE

Thomas G. Moore, Chairman; Carroll A. Garner, Vice-Chairman; George B. Carless, F. W. Hanson, Albert J. Phillips, Lloyd C. Gibson, R. D. Mallison, John T. Sherman. Alternates, A. C. Brinker, H. W. Hitzrot, Plato Malozemoff, Ivan Given, T. D. Jones, W. H. Farrand.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend privileges but does not desire to admit persons unless they are qualified. Objections on applications should be received on the 15th of the month following publication in PETROLEUM TECHNOLOGY.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; AM, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

CALIFORNIA

Banning — Hansen, Beauford V. (J) (C/S-S-J).
Berkeley — Dunasky, John F., Jr. (J) (C/S-S-J).
La Jolla — Barbarick, Harding (J).
Riverdale — Gibson, Lee W. (M) (C/S-A-M).

COLORADO

Loveland — Weaver, Lewis K. (J).

ILLINOIS

Effingham — Burke, Billy F. (J).
St. Charles — Sheldon, John A. (J) (C/S-S-J).

KANSAS

Wichita — McGuire, Edward M. (J) (R, C/S-S-J); Sells, Harold R. (M) (C/S-A-M).

LOUISIANA

Harvey — Trueblood, Harry A. Jr. (J).
Houma — Sylvester, Burke (J).
Lafayette — Johnston, Richard E. (M).
Lake Charles — Cummings, Aaron (J).
New Iberia — Kizer, Curtis A. (A).

OKLAHOMA

Bartlesville — Dolman, Jack A. (M).

PENNSYLVANIA

Bradford — Sittig, William R. (J) (C/S-S-J).
Cresson — Bartlebaugh, Dale L. (J) (C/S-S-J).
State College — Calhoun, John C. (M); Hill, Trevor W. (J).

TEXAS

Corpus Christi — Whitmire, William A. (J).
Dallas — Grubb, William E. (J).
Fort Worth — Acklin, Floyd, Jr. (J); Tinslar, William L. (J) (R, C/S-S-J).
Houston — Brooks, Aubrey J., Jr. (J) (C/S-S-J); Ray, Millard L. (M); Yust, Charles S. (M) (C/S-A-M).
Levelland — Edwards, Floyd C. (M) (C/S-J-M).
Lubbock — Buckner, Roy E. (J) (C/S-S-J).
McKinney — Abbott, Seth J. (J).
Pampa — Losher, Don J. (J) (C/S-S-J).

CANADA

Alberta — Stout, Kenneth R. (J).

SAUDI ARABIA

Dhahran — Conroy, John Patrick (J) (C/S-S-J). ★ ★ ★

Petroleum Technology Adds Representative

The firm of William R. Stewart, publisher's representatives, has been retained by the Petroleum Branch to act in the Midwest area in the solicitation of advertising for the JOURNAL OF PETROLEUM TECHNOLOGY. The Stewart organization will operate for PETROLEUM TECHNOLOGY in Illinois, Wisconsin, Michigan, Indiana, Ohio, Kentucky, Minnesota, Iowa, Missouri, Kansas and Nebraska. Main offices of the Stewart Co. are at 9 S. Clinton St., Chicago, Ill.

With the conclusion of this transaction, representation for the JOURNAL OF PETROLEUM TECHNOLOGY is now complete in all major petroleum equipment manufacturing areas of the United States. The magazine is represented in the Southwest and West by the firm of McDonald-Thompson and in the East by Allen Associates.

At the present, advertising on contract for 1951 amounts to a little more than $29,000.00. For the present accounting the publication is budgeted for $27,000.00 income from advertising. It is estimated that income from advertising will exceed $30,000.00 for 1951, an increase of about 60 per cent over similar income in 1950. ★ ★ ★

Manpower Commission Issues First Bulletin

Bulletin 1 of the Engineering Manpower Commission of Engineers Joint Council, entitled "Utilizing Engineering Manpower . . . Deferment Procedures," was issued recently. It is a 14-page pamphlet, discussing the selection and utilization of technical personnel, special Selective Service procedure pertaining to college students and current college graduates, general occupational deferment procedures under Selective Service for non-reservists, recall of reservists to active duty, and giving other pertinent information for engineering employers and employes. Copies have been supplied to all Local Section Secretaries, or will be supplied at 25c each on individual order to Engineering Manpower Commission, 11th Floor, 29 W. 39th St., New York 18, N. Y. ★ ★ ★

AGI Reproduces Article On Conserving Manpower

The American Geological Institute has made available in the public interest reprints of the article, "Manpower—The Most Important Factor in Defense Mobilization," which appeared in the May issue of the JOURNAL OF PETROLEUM TECHNOLOGY. The article presents a basic formula for conserving manpower in the best interests of both the military and industry. It reports on the current policy of the armed forces concerning selectees and reserve personnel, and outlines a procedure for industry to follow in obtaining deferments for essential employees. The author, E. W. Berlin, is chairman of the API Defense Services Committee, a member of the National Petroleum Council's Manpower Committee, and a colonel in the U. S. Air Force Reserve. Copies of the article may be obtained from the American Geological Institute, 2101 Constitution Avenue, Washington 25, D. C. A limited supply is also available in the office of the Petroleum Branch, AIME, Dallas. ★ ★ ★

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Book Reviews

Marine Geology

By Ph. H. Kuenen, John Wiley & Sons, Inc., New York, 1950. 551 pp., diagrs., charts, maps, tables, 9¼x6¼ in., cloth, $7.50.

This book summarizes geological matter with regard to submarine landforms and their interpretation, sedimentary cover of the sea floor, the structure of atolls, etc. Present sedimentation processes and the evidence of conditions during accumulation that may be expected in ancient sediments are presented. Emphasis is placed on problems and relations rather than descriptions of properties, distributions, and numerical data. The author gives special attention to coral reefs, submarine canyons and the Moluccan deep-sea troughs, as topics with which he is especially familiar.

Unit Operations

By George Granger Brown and Associates, John Wiley & Sons, Inc., New York, 1950. 611 pp., illus., diagrs., charts, tables, 11¼x8¾ in., cloth, $7.50.

This book is a comprehensive treatment of modern process operations, stressing the similarity of their basic principles, in order to clarify the problems of design and operation of processing equipment. A common nomenclature is used throughout in similar theoretical discussions. The operations are divided into four groups: solids, fluids, separation by ideal or equilibrium stages, and rates of energy and mass transfer. Large illustrations and charts, as well as derivation of theoretical equations and descriptions of important equipment, increase the book's usefulness. ★ ★ ★

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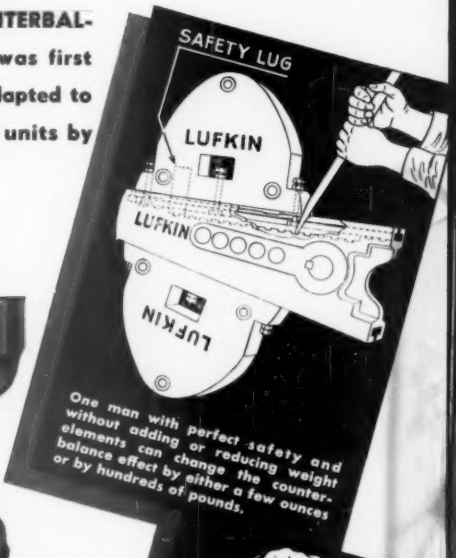

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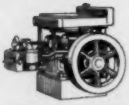

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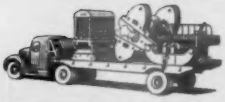

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